MICE:
The Trackers and Magnets

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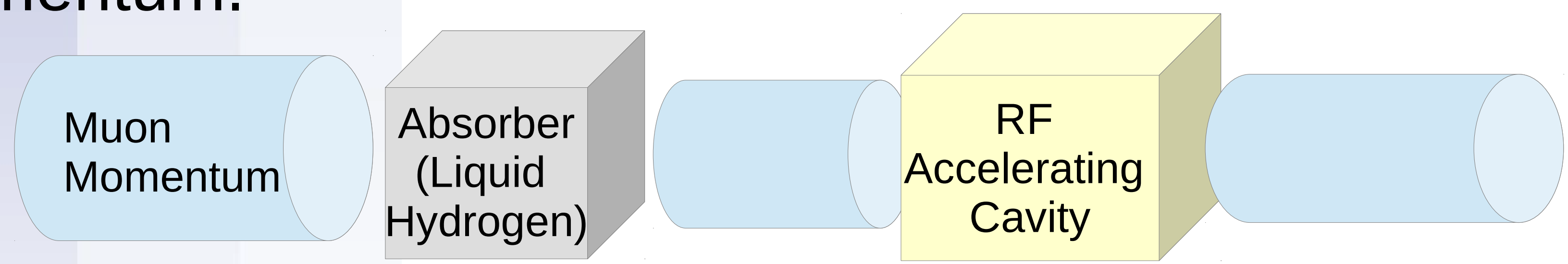
What is Muon Ionisation Cooling?

- A muon beam loses both transverse and longitudinal momentum by ionisation when passed through an `absorber'
- The lost longitudinal momentum is then fully/partially restored by RF cavities.
- The result is a beam of muons with reduced transverse momentum.



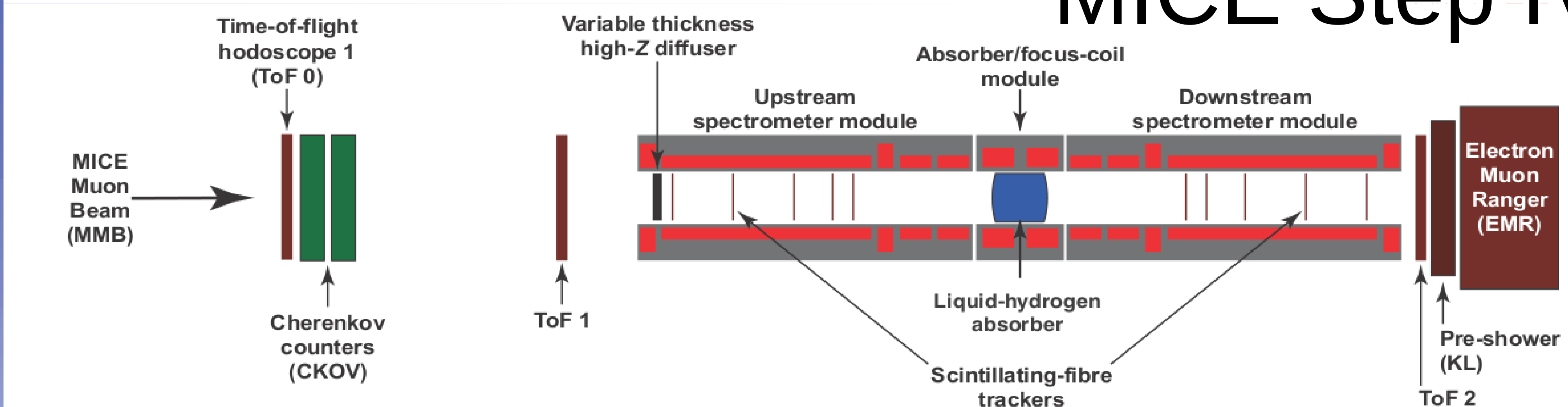
- However, this process also causes some heating due to multiple scattering so the net cooling is a delicate balance between these two effects:

$$\frac{d\epsilon_n}{ds} \sim -\frac{1}{\beta^2}\left\langle\frac{dE_\mu}{ds}\right\rangle\frac{\epsilon_n}{E_\mu} + \frac{1}{\beta^3}\frac{\beta_\perp(0.014\mathrm{GeV})^2}{2E_\mu m_\mu L_R}$$

Motivation: Summary

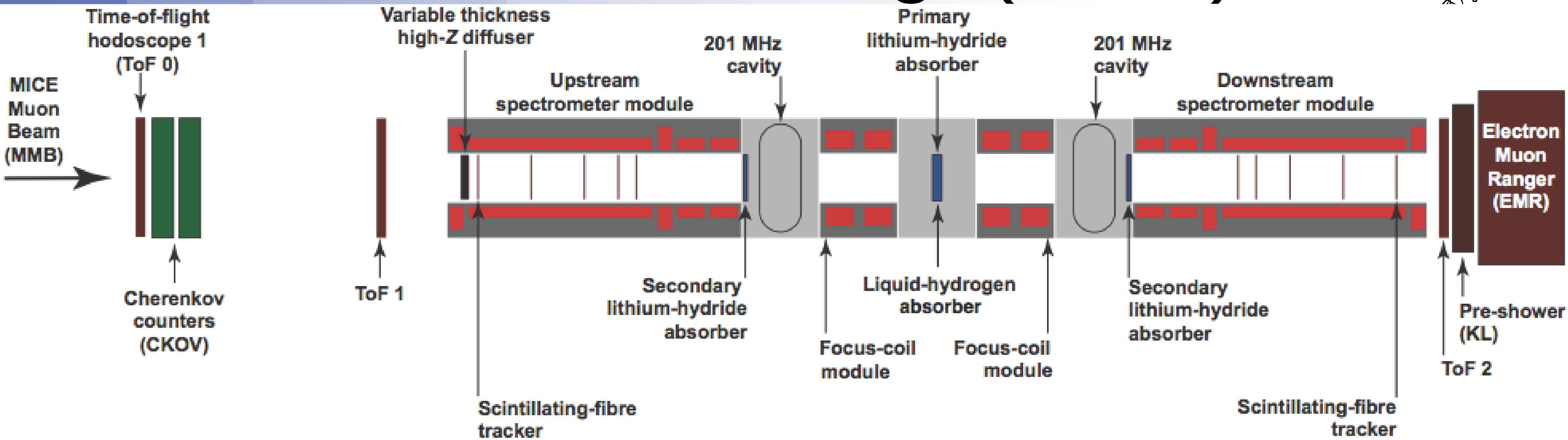
- Muon colliders and neutrino factories are attractive options for future facilities aimed at achieving the highest lepton-antilepton collision energies and precision measurements of parameters of the Higgs boson and the neutrino mixing matrix.
- Performance and cost depends on how well a beam of muons can be “cooled”.
- MICE has developed and will test a full or partial cooling cell, a series of which would be used to produce the collider or neutrino factory.
- Short lifetime of muon means that
  - traditional beam cooling techniques which reduce emittance cannot be used.
  - ionisation cooling is the only practical solution to preparing high intensity muon beams for use in these facilities.
- MICE is currently the only experiment studying ionisation cooling of muons.
- Recent progress in muon cooling design studies and prototype tests nourishes the hope that such facilities can be begin to be built during the next 20 years.

MICE Step IV



- Includes the two solenoidal spectrometers, a pair of alternating focus coils (field flips at centre), and an absorber (liquid-hydrogen, lithium-hydride etc);
- allows normalised emittance change of beam passing through an absorber to be measured (before and after the absorber by the Trackers),
- over a range of momenta and under a variety of focusing conditions.
- However, it will lack the crucial RF re-acceleration required for “sustainable” cooling (lost energy is not restored hence cooling cannot be iterated).
- **Data taking for calibration and commissioning has begun!!!**

MICE: Demonstration of Ionisation Cooling (2017)



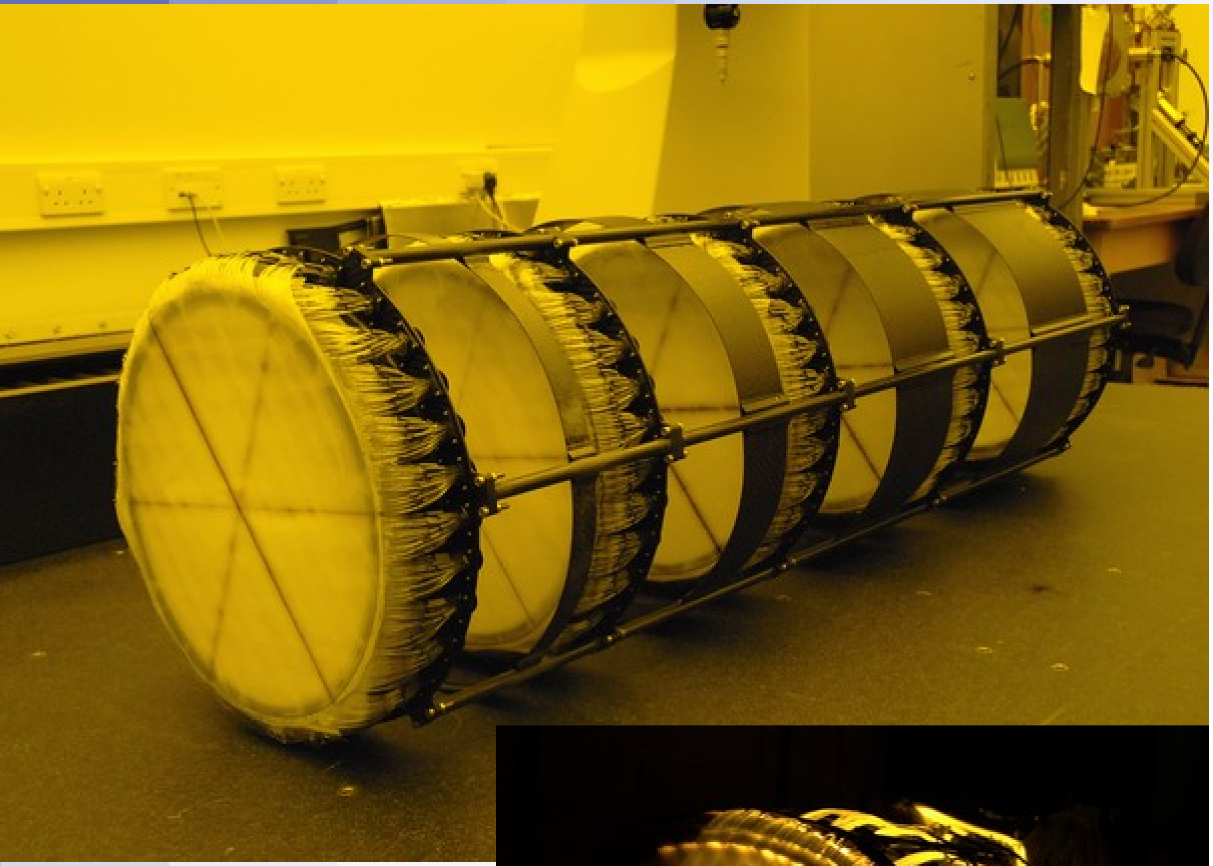
- The cooling section contains one full absorber, plus two secondary absorbers which protect the tracking devices from radiation emitted by the RF cavities and also increase the measured cooling factor.
- The baseline magnetic configuration of the cooling section is referred to as “FOFO” and is such that the magnetic field reverses (“flips”) at the centre of the central absorber.
  - Periodic field reversal is essential for a full-length cooling channel in order to prevent growth of canonical angular momentum.

The Detectors

- Time Of Flight: TOF0, TOF1 and TOF2
- Electron Muon Ranger: EMR
- KLOE-Light: KL
- Cerenkov: CkoVa CkoVb

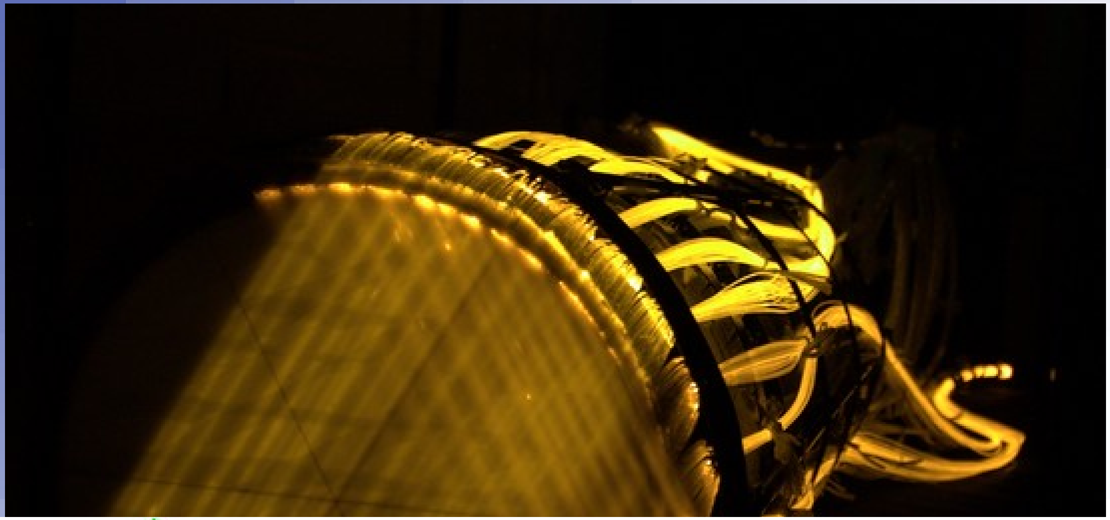
- Trackers
  - 2 Tracker detectors upstream and downstream of cooling section, each immersed in a uniform magnetic field of 4T.
  - Measure the normalised emittance precision to 0.1% (beam emittance measured before and after cooling).

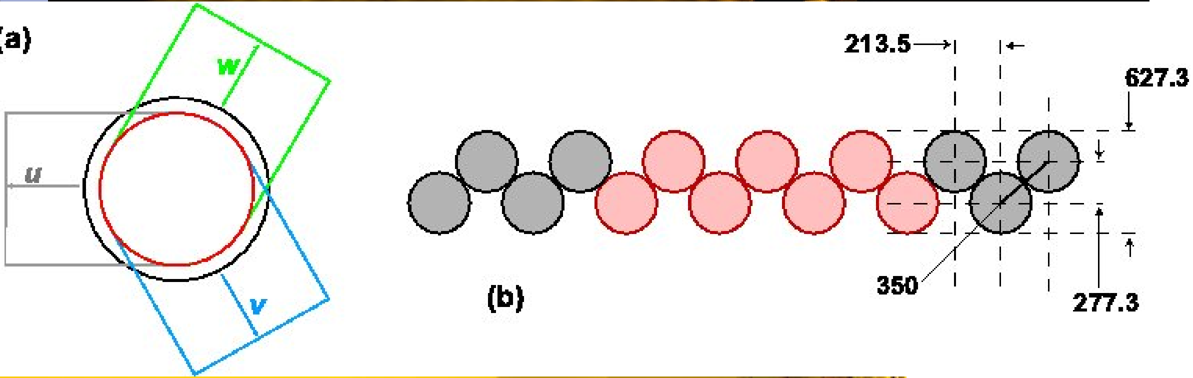
The Trackers



- Two scintillating fibre trackers, one upstream, one downstream of the cooling channel.
- Each within a spectrometer solenoid producing a 4T field.
- Each tracker is 110 cm in length and 30 cm in diameter.
- 5 stations
  - varying separations 20-35 cm (to determine the muon pT).
- 3 planes of fibres per station each at 120°.
- LED calibration system.
- Hall probes.

The Trackers



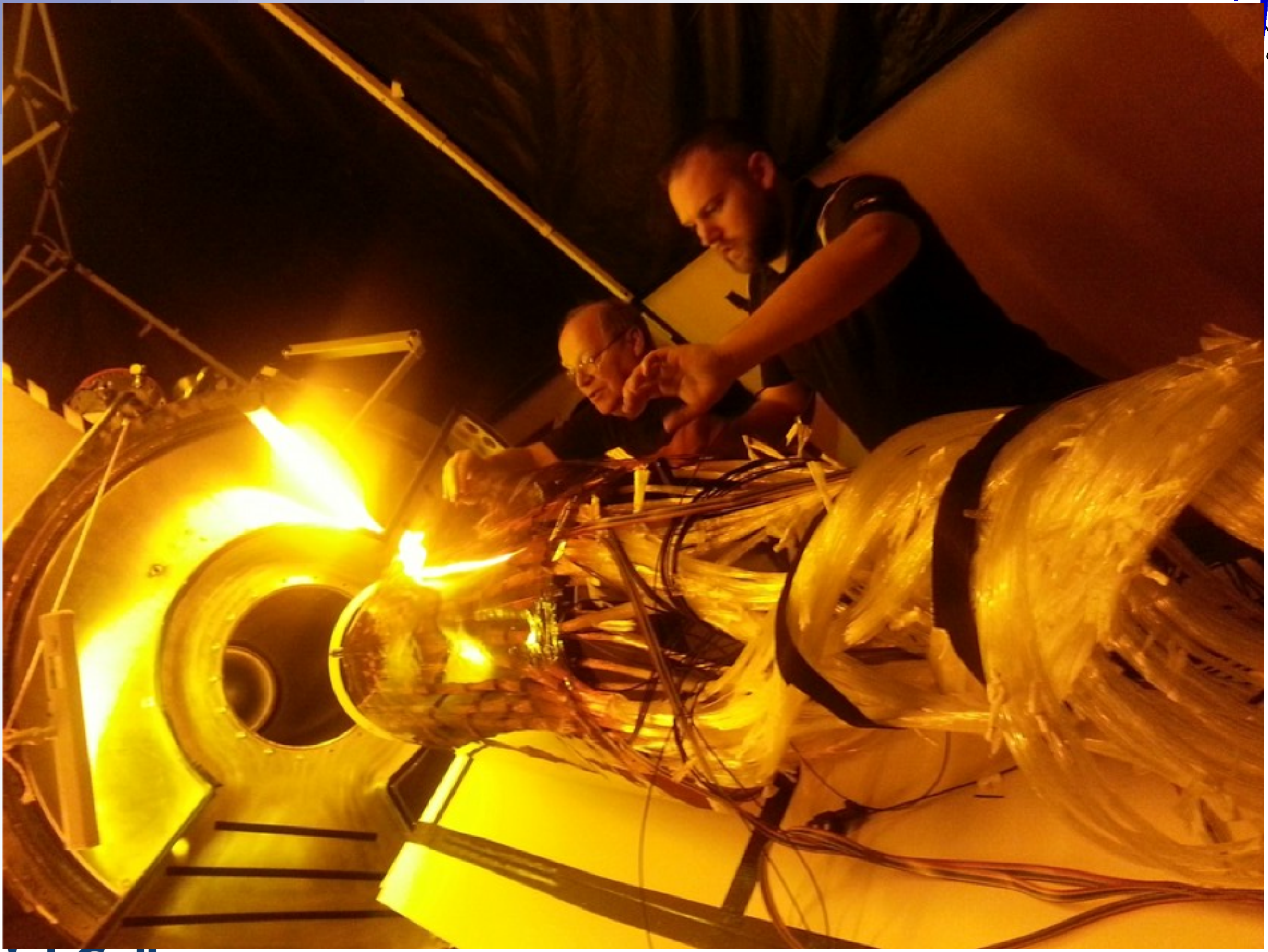


- 350 µm scintillating fibres are glued into doublet layers (planes)
  - Thickness: 627µm (a).
- 7 fibres are grouped into a single readout channel (b). (This reduces the number of readout channels, while maintaining position resolution).
- Position resolution: 470 µm.

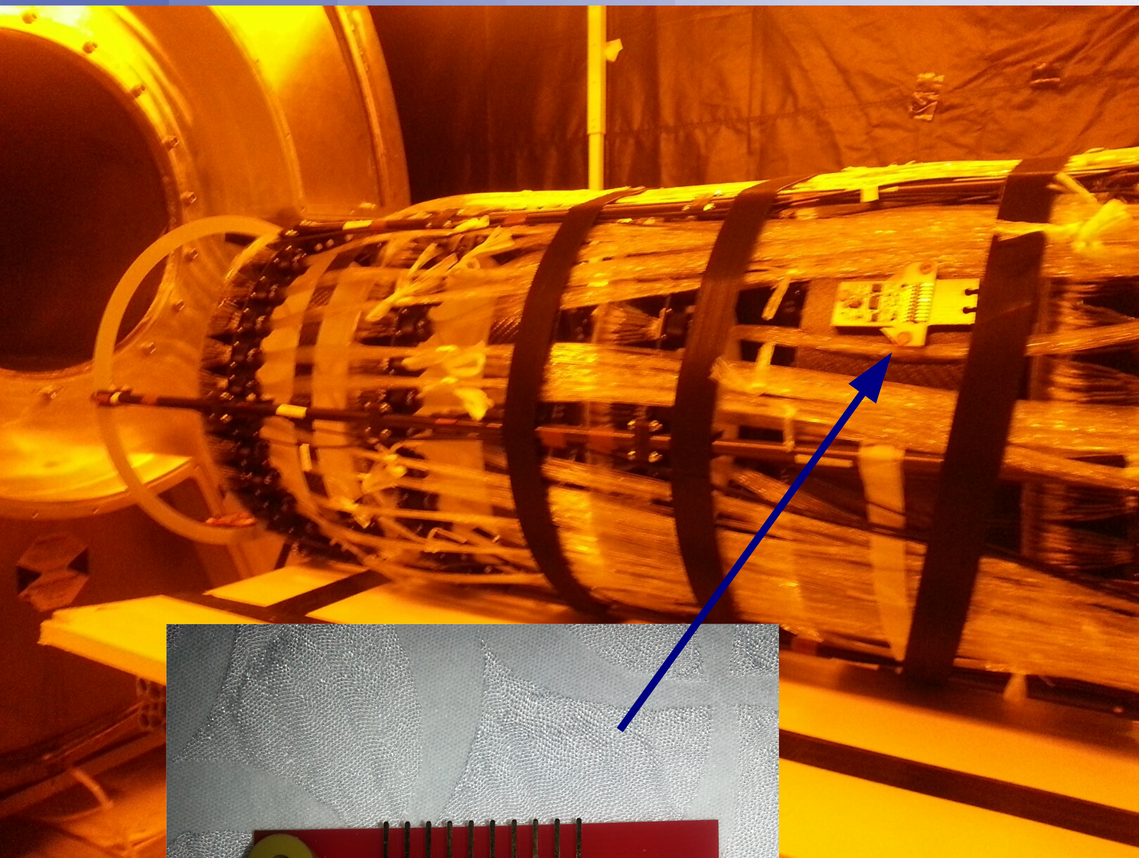
Tracker Installation

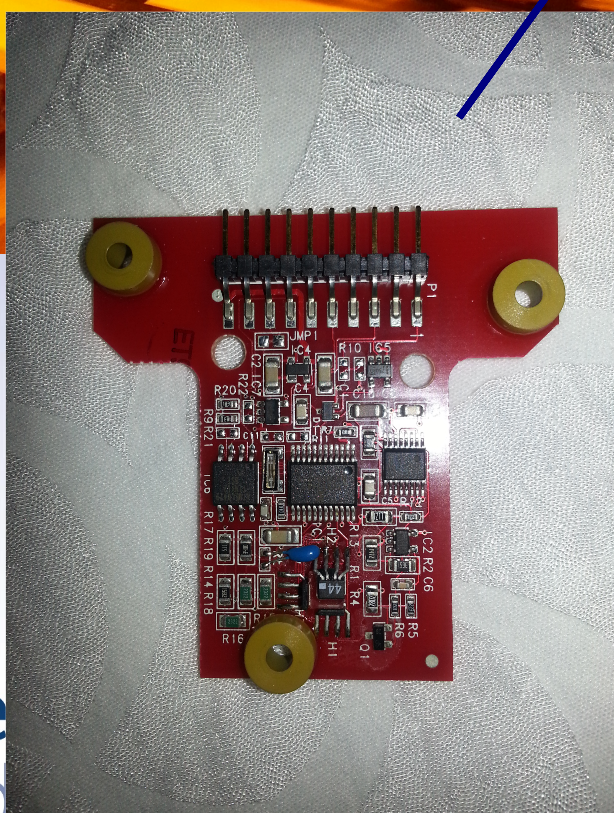
Trackers are sensitive to light < 450 nm....

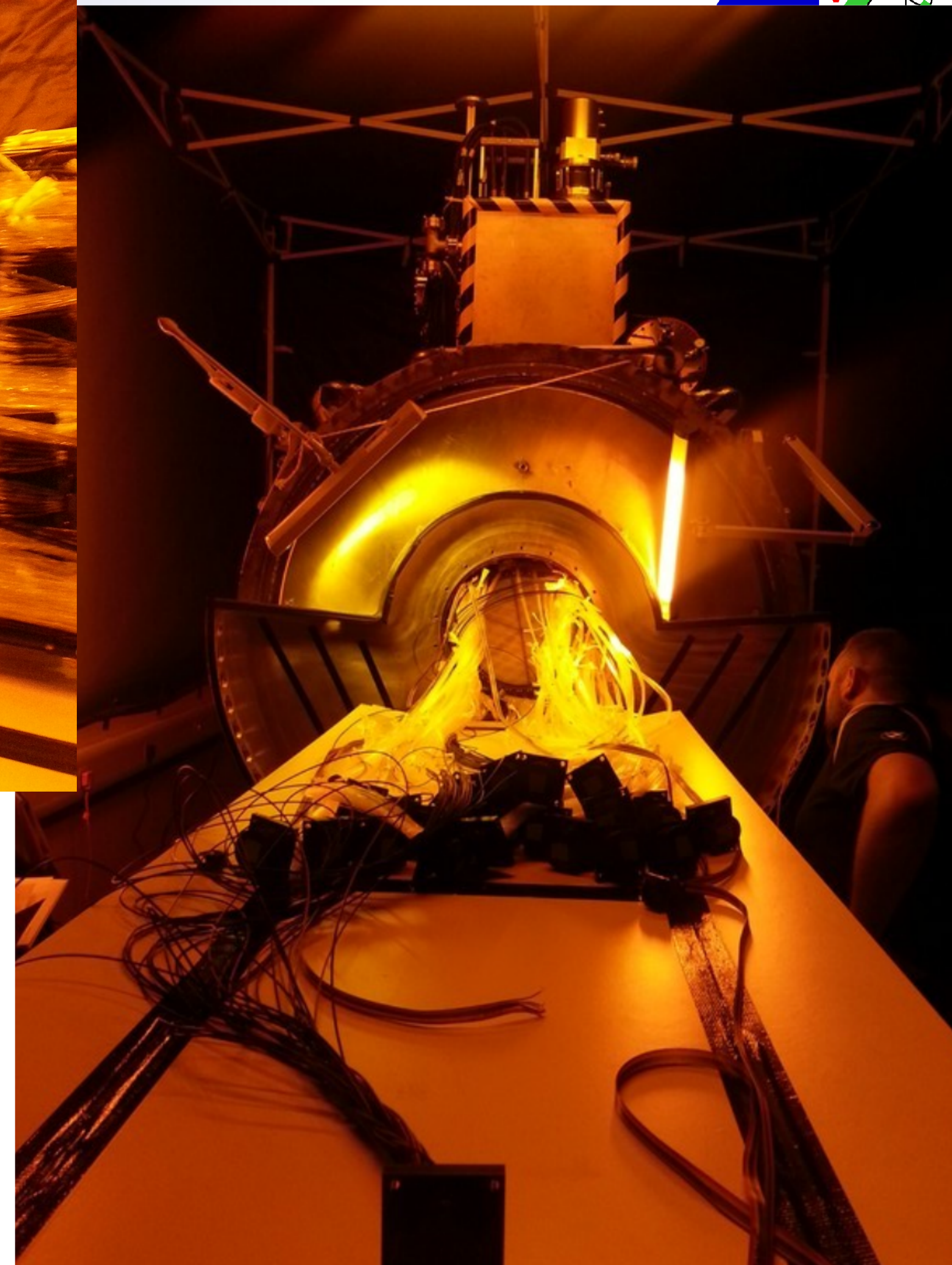
Tracker Installation

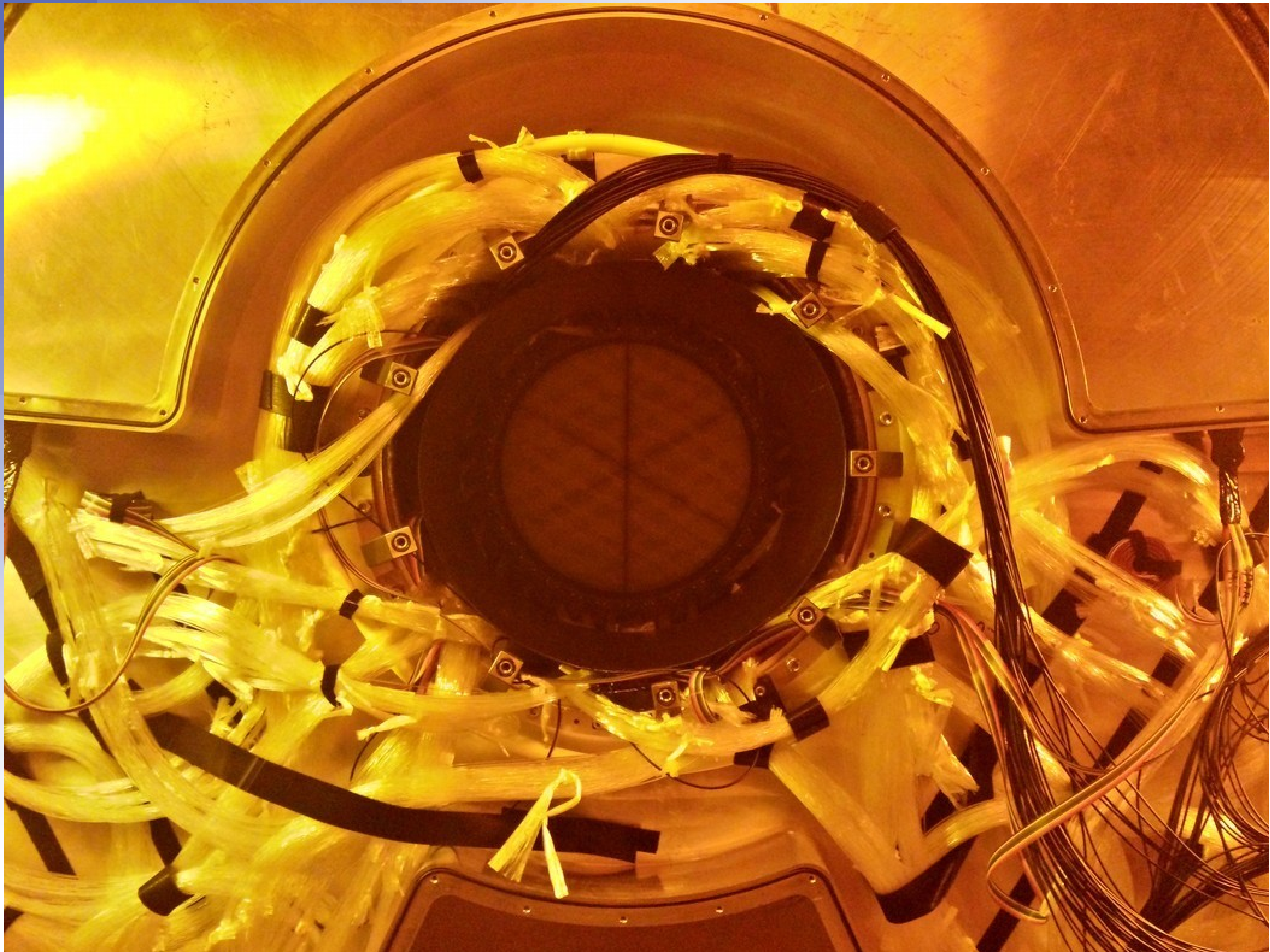


Tracker Installation

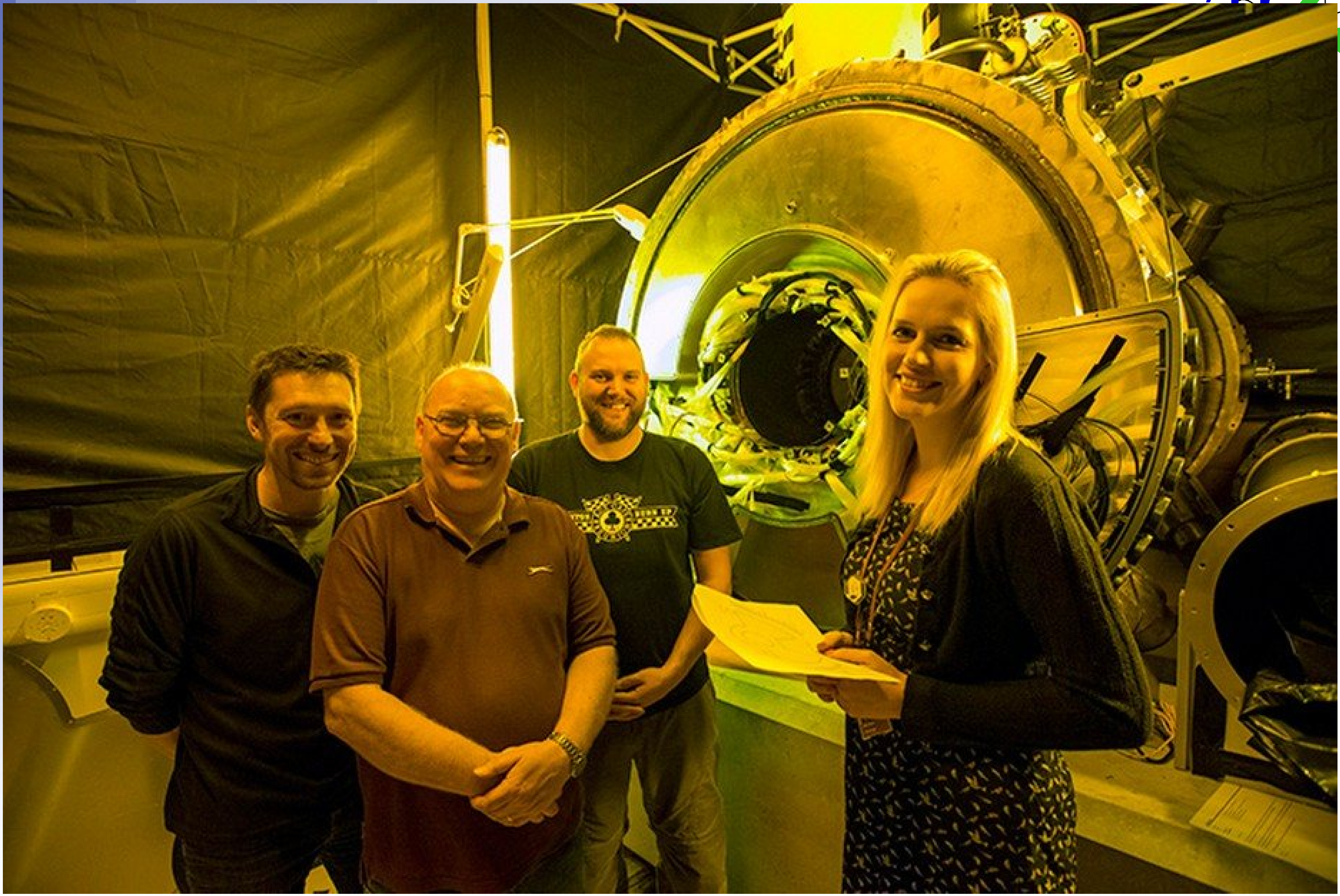




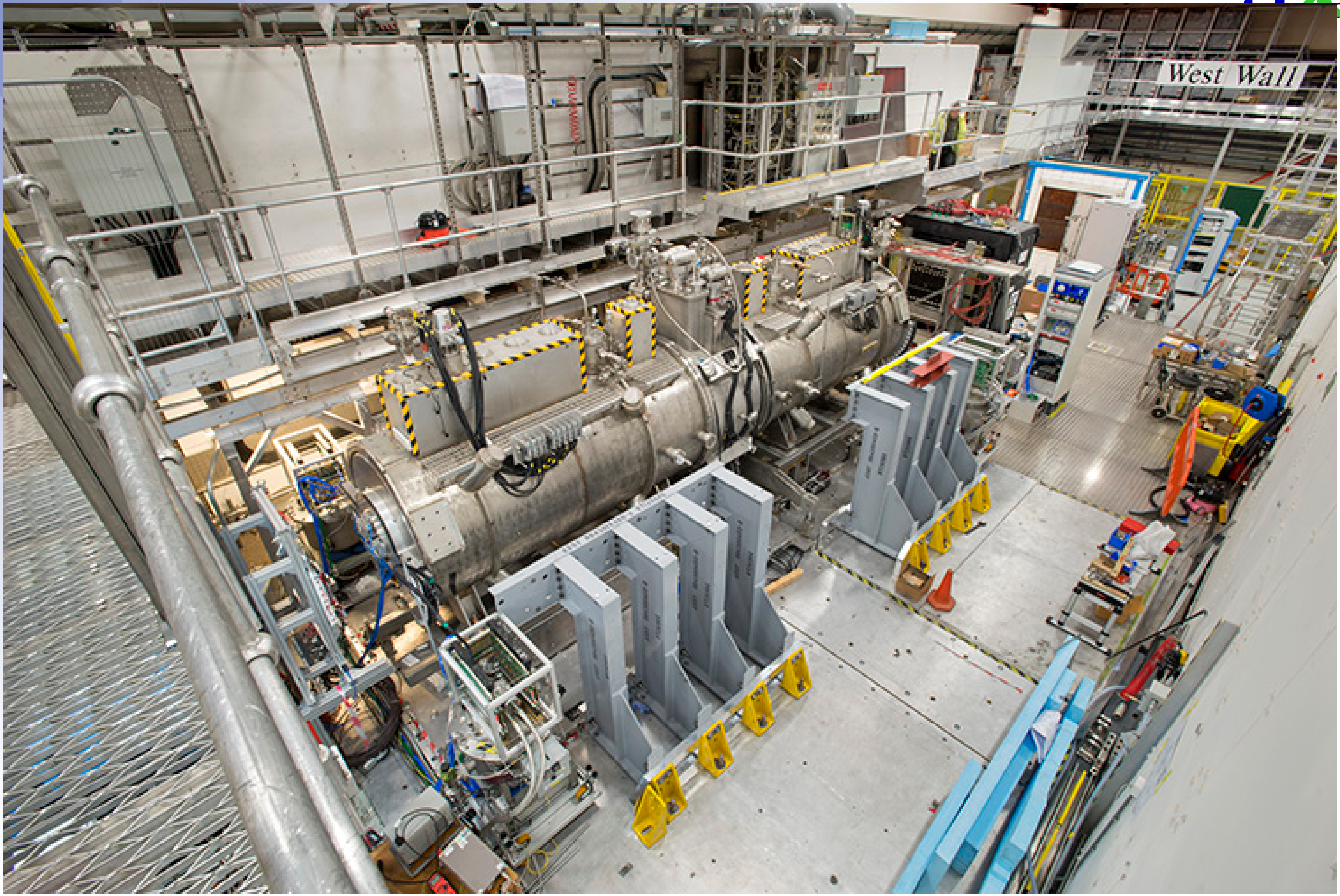




Tracker Installation



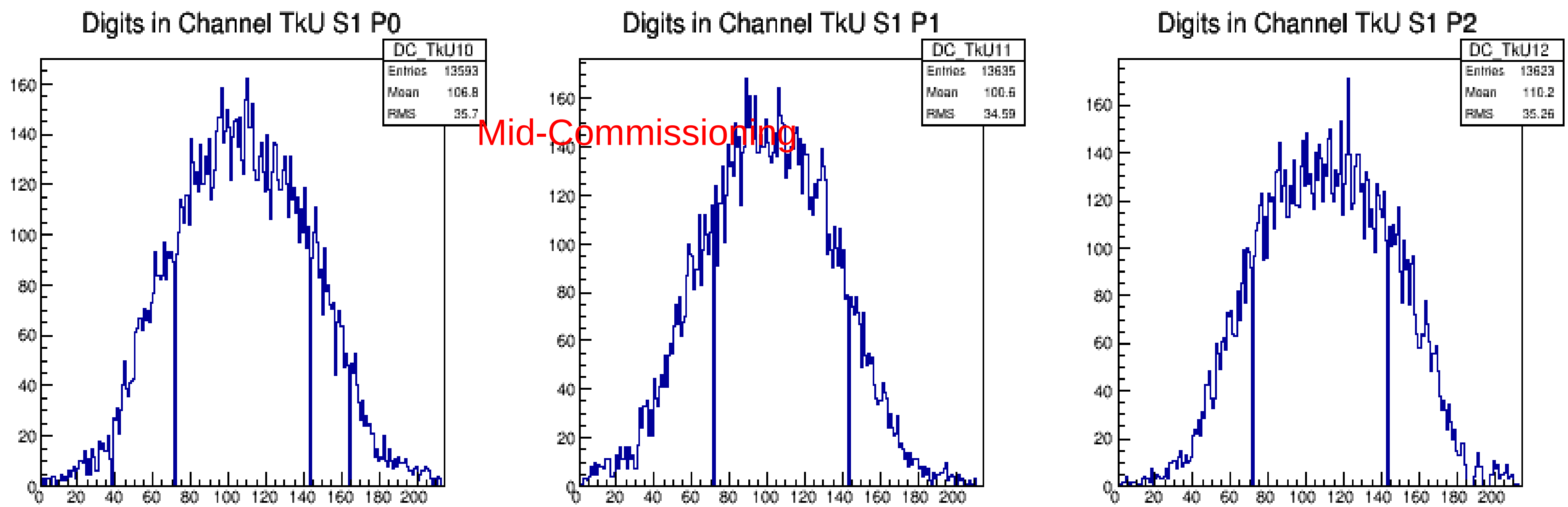
In The MICE Hall



Tracker Readout

- Light carried from trackers via external waveguides (lightguides).
  - 1 mm clear fibres.
  - 152 fibres per waveguide.
  - 13 waveguides per cryostat.
- Fibres readout by Visible Light Photon Counters
  - operating at liquid He temperatures.
- Digitised by FPGA based system from D0.

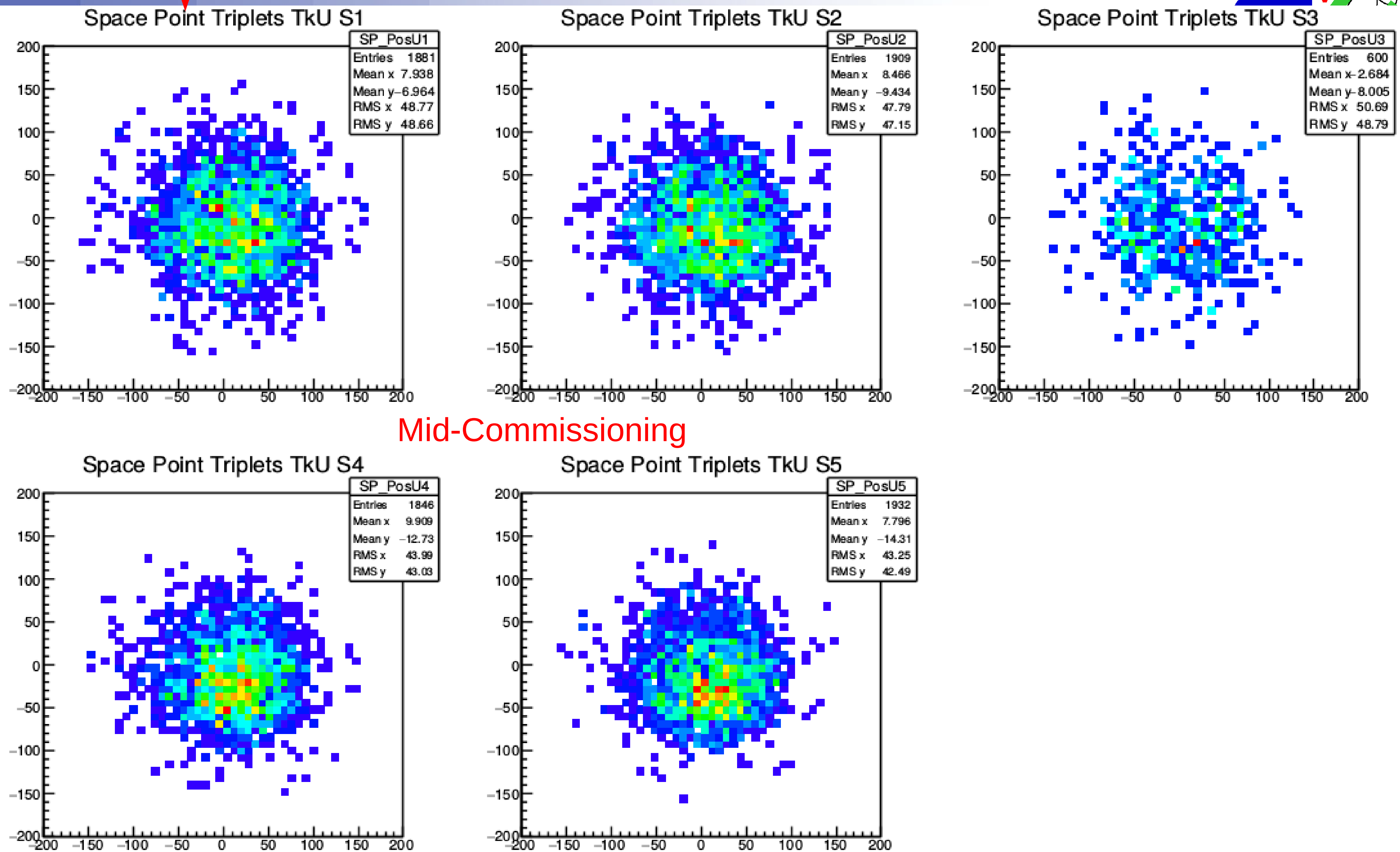
Tracker Commissioning
Hits in the 3 Planes of Stn 1 US



Dead channels and electronics problems are identified and corrected by considering low level reconstruction objects eg hits.

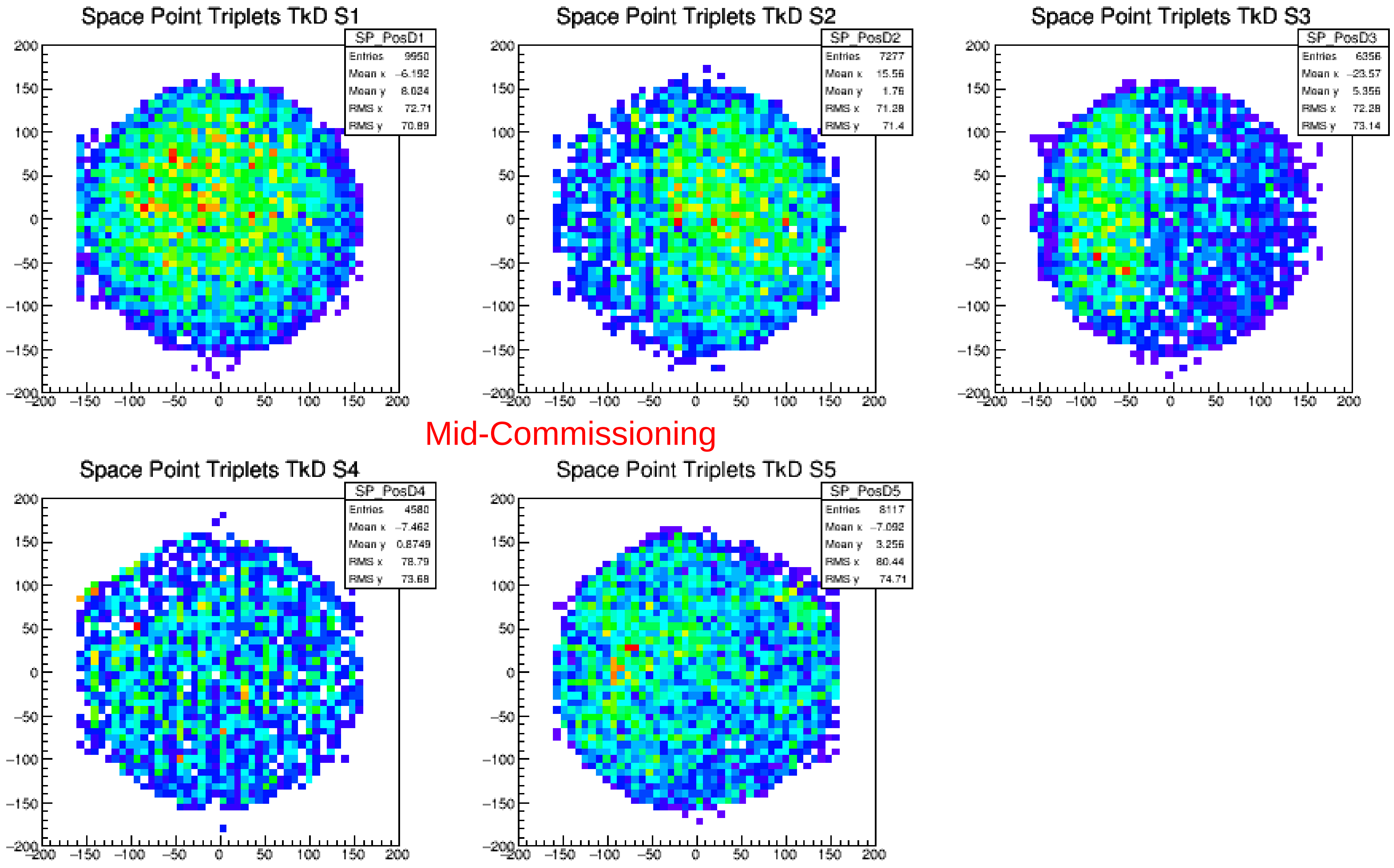
US Tracker Commissioning

Nearest to absorber

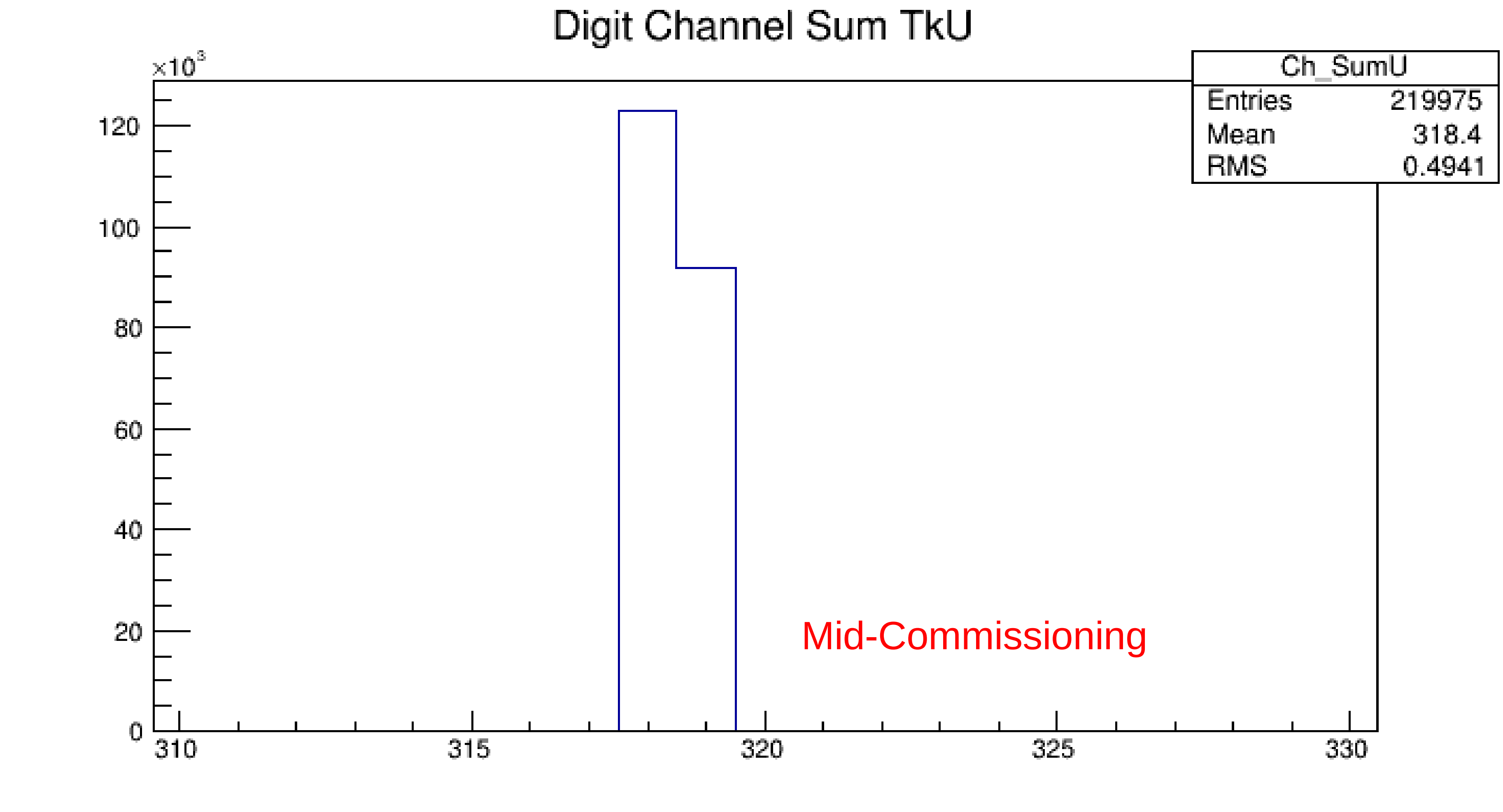


DS Tracker Commissioning

Nearest to absorber

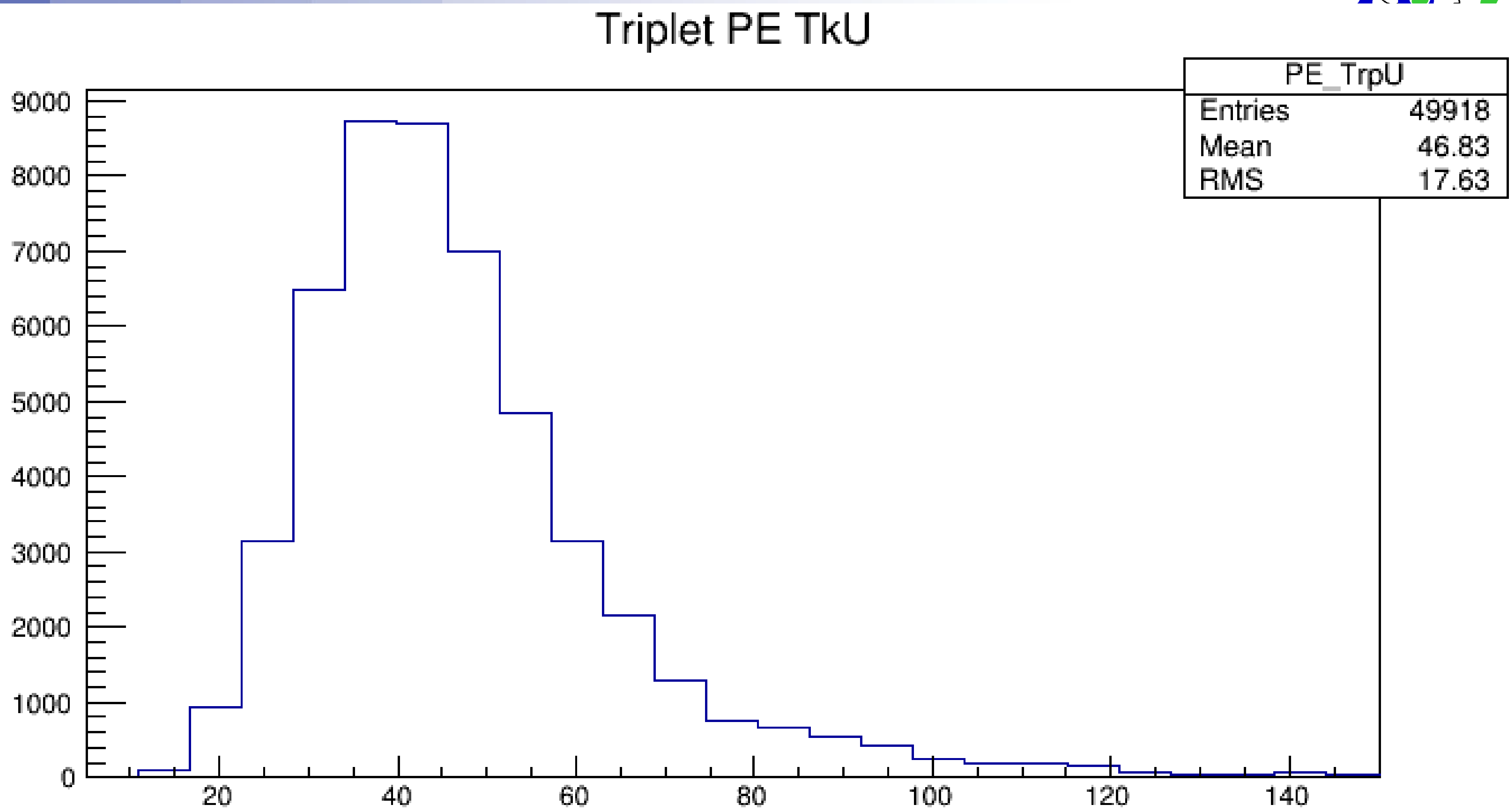


Sum of Channels Hit

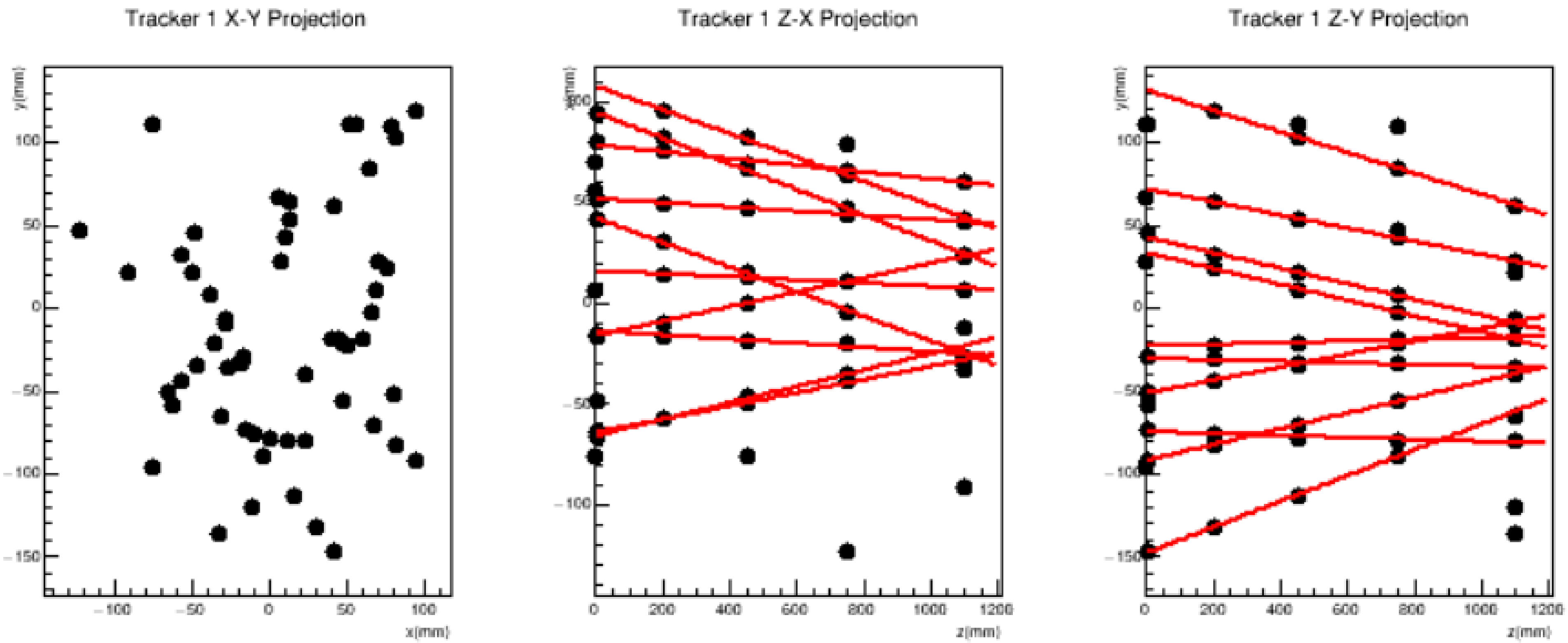


Should add up to 318 → indicates the waveguide/channel mapping is accurate.

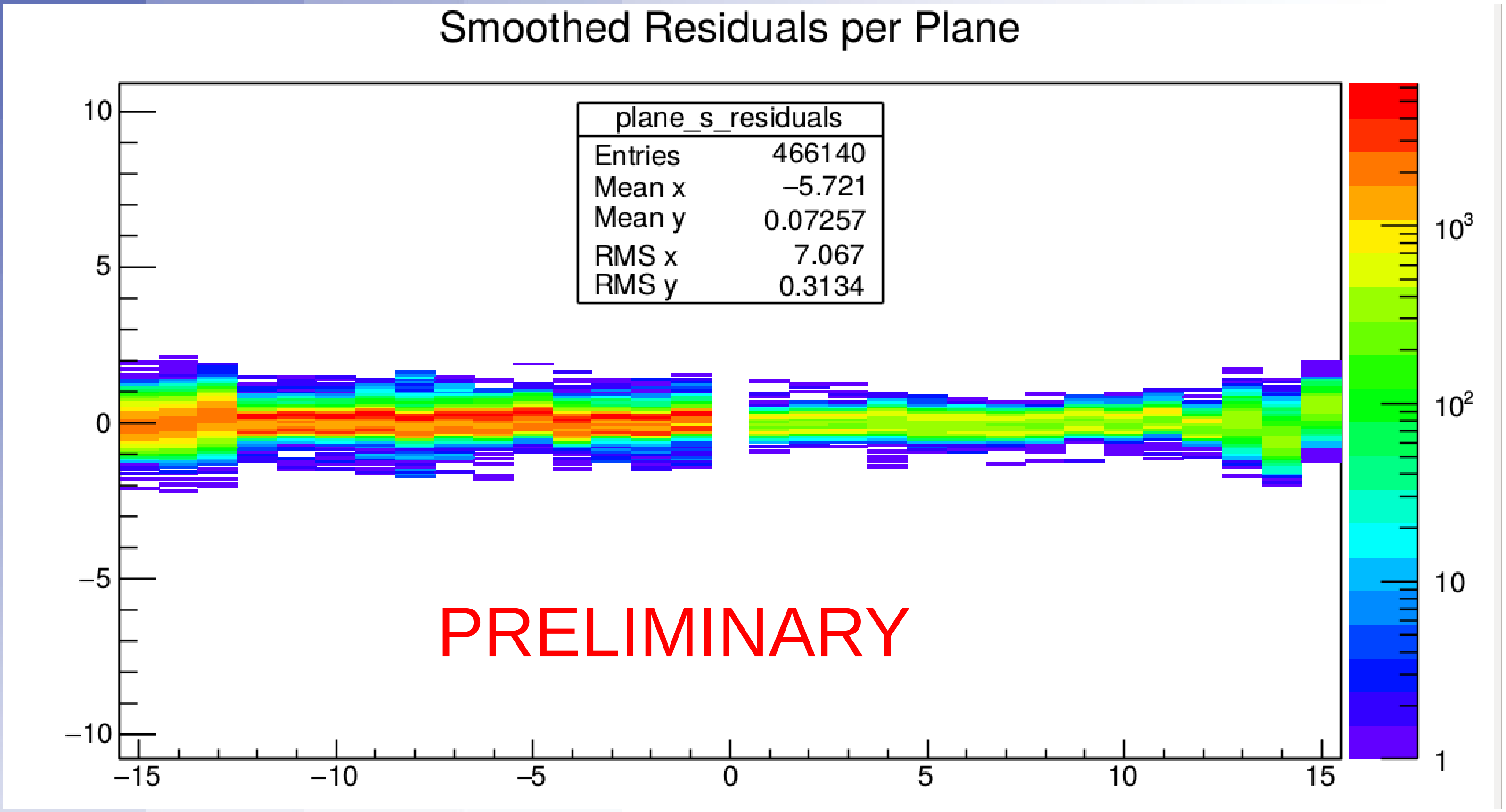
Pe in Upstream Tracker



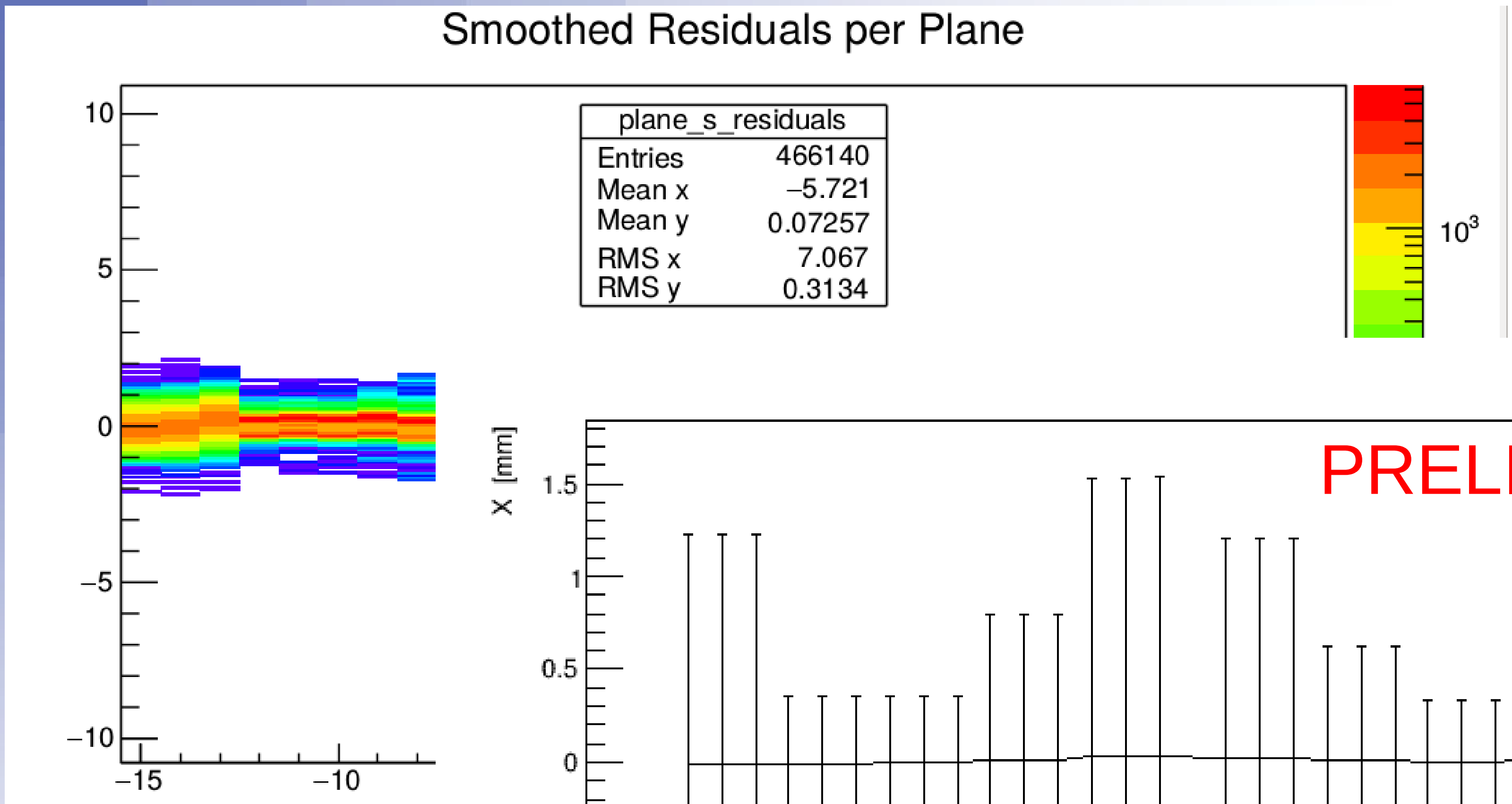
Tracker Data First Tracks! (No field)

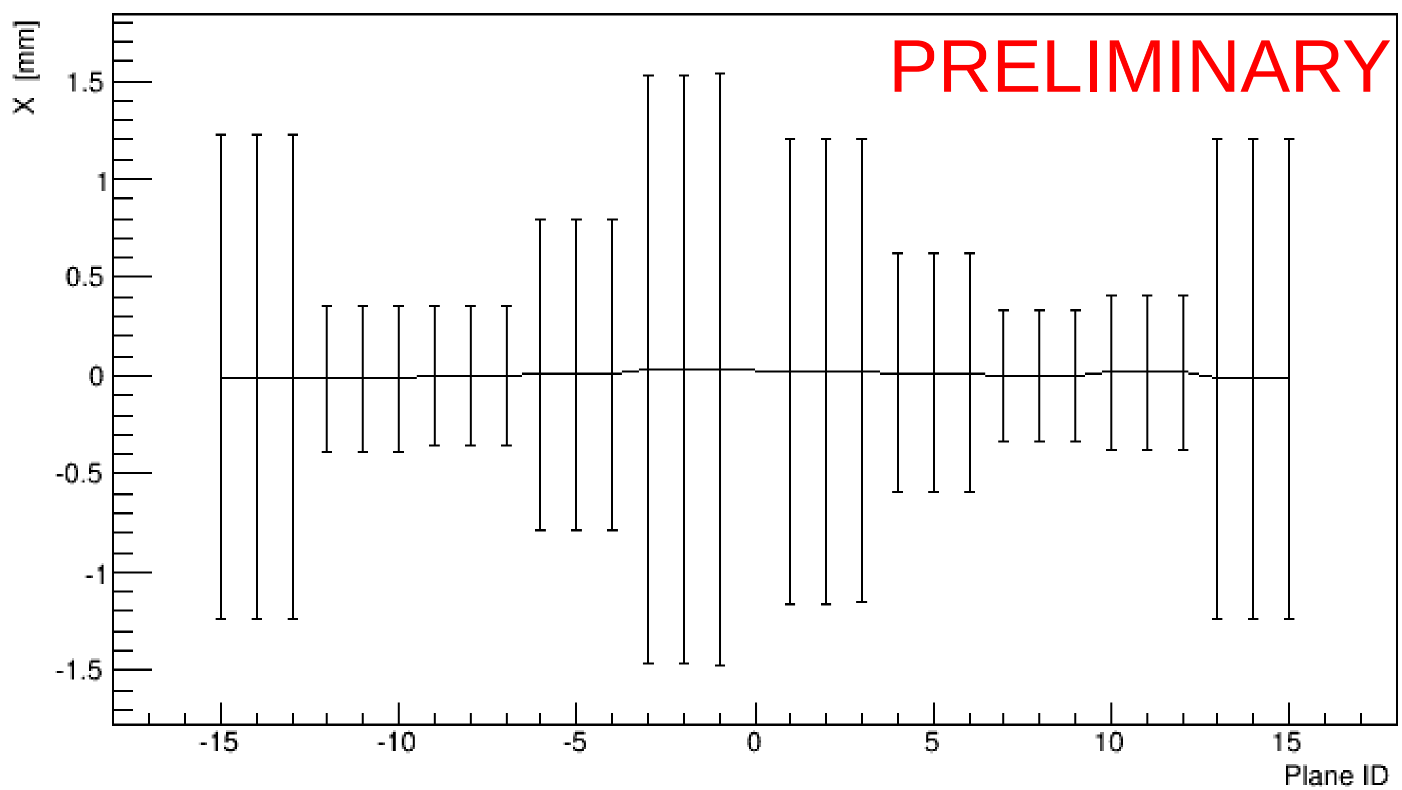


Tracker Alignment (Kalman)

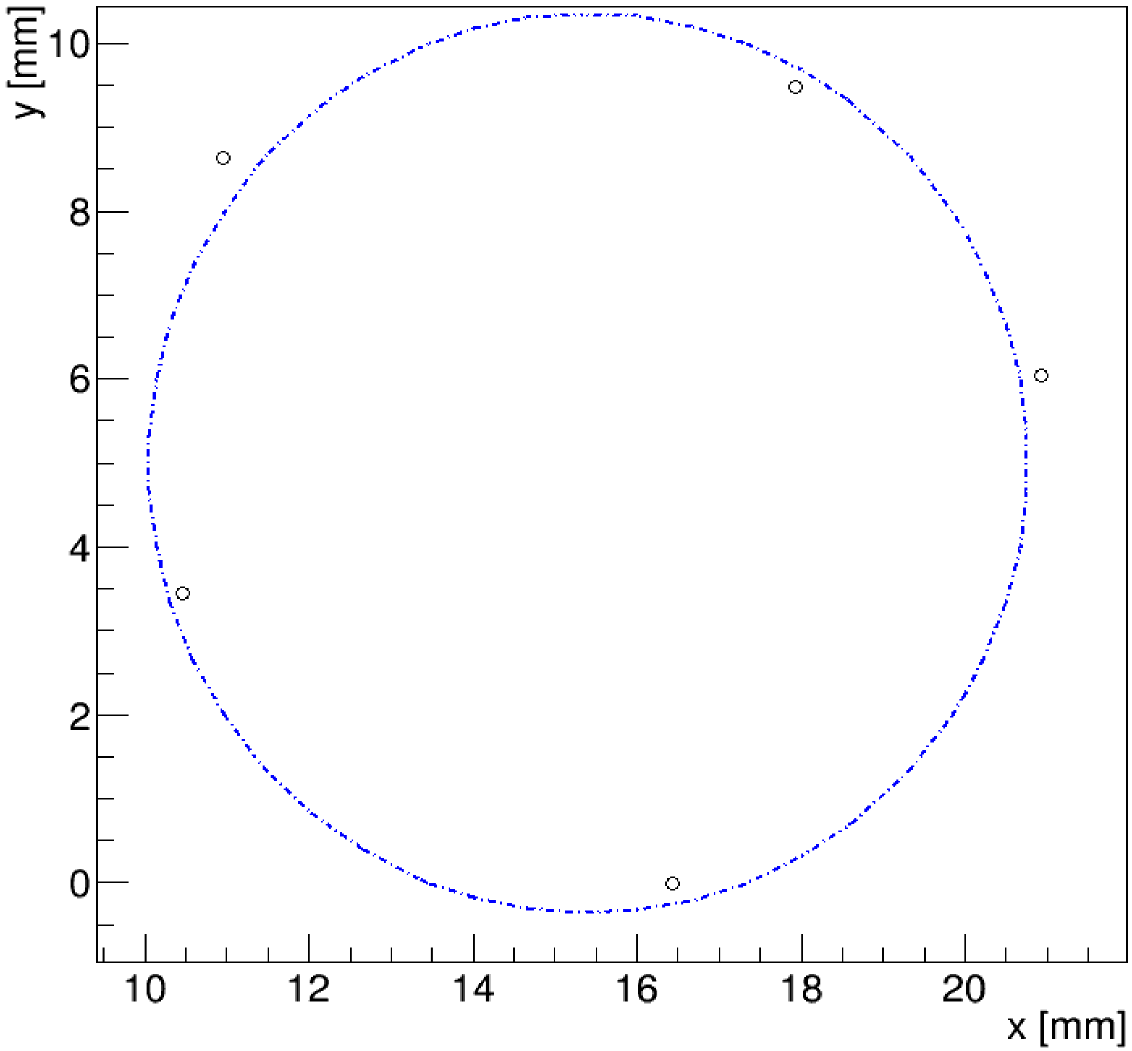


Tracker Alignment (Kalman)





Tracker Data First Helical Tracks!

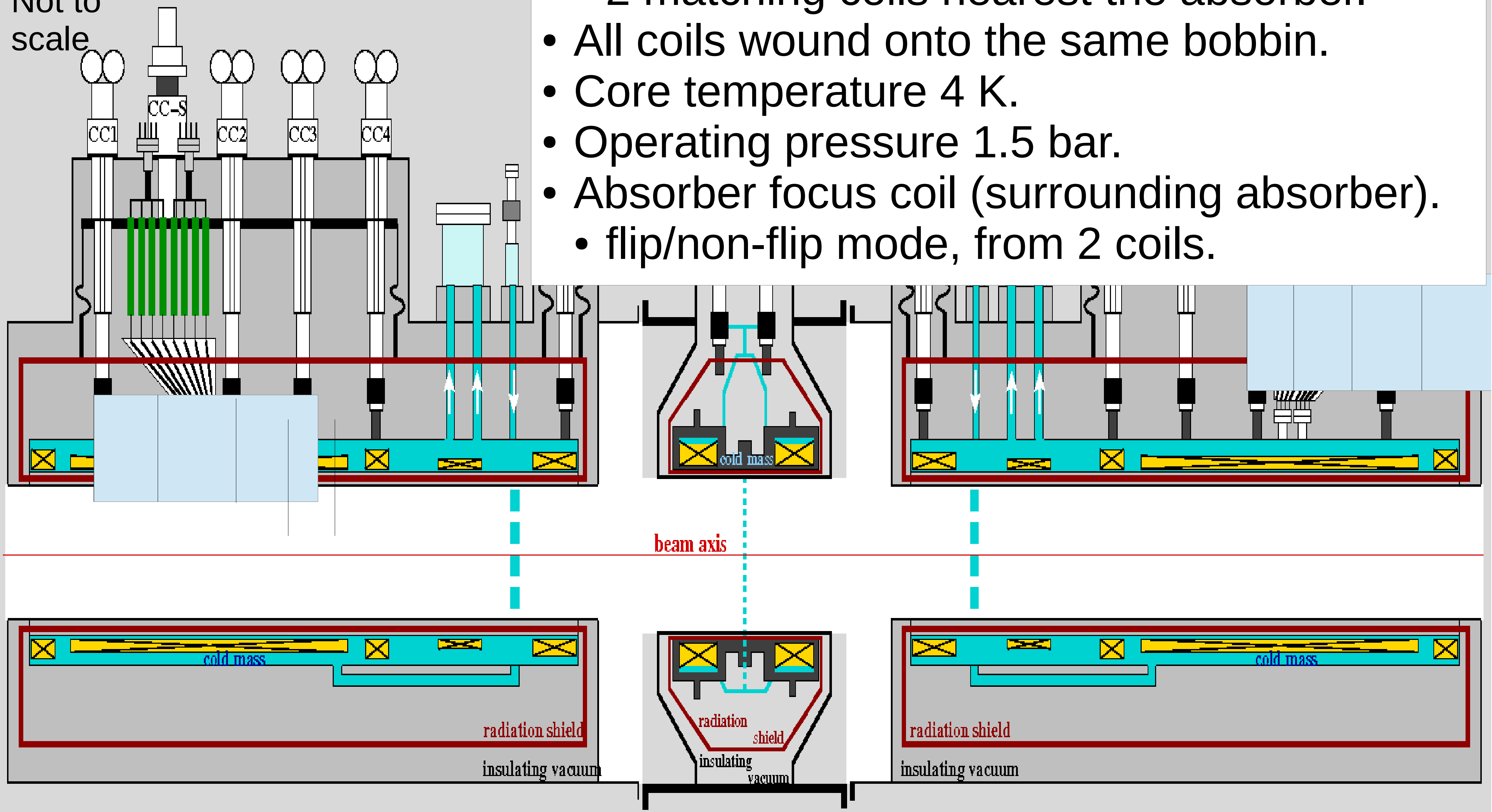


Reconstructed spacepoints showing a particle making a helical trajectory in the Downstream Tracker

The Magnets

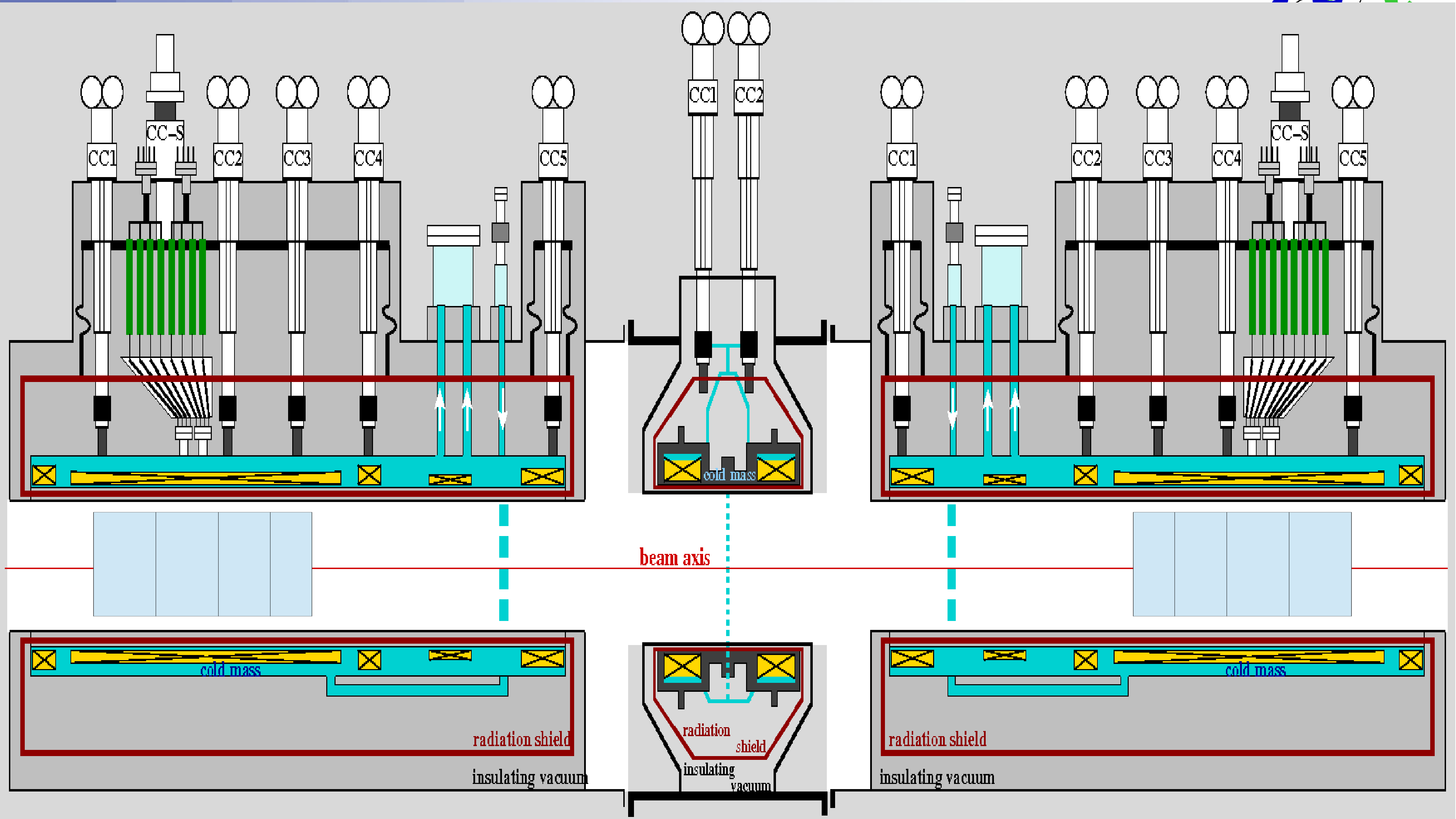
- Two Spectrometer solenoids.
- Produce a 4 T magnetic field.
- 5 coils in each spectrometer solenoid:
  - Central coil which covers the Trackers.
  - 2 end coils either side of the central coil.
  - 2 matching coils nearest the absorber.
- All coils wound onto the same bobbin.
- Core temperature 4 K.
- Operating pressure 1.5 bar.
- Absorber focus coil (surrounding absorber).
  - flip/non-flip mode, from 2 coils.

Not to scale



The Magnets

Not to scale

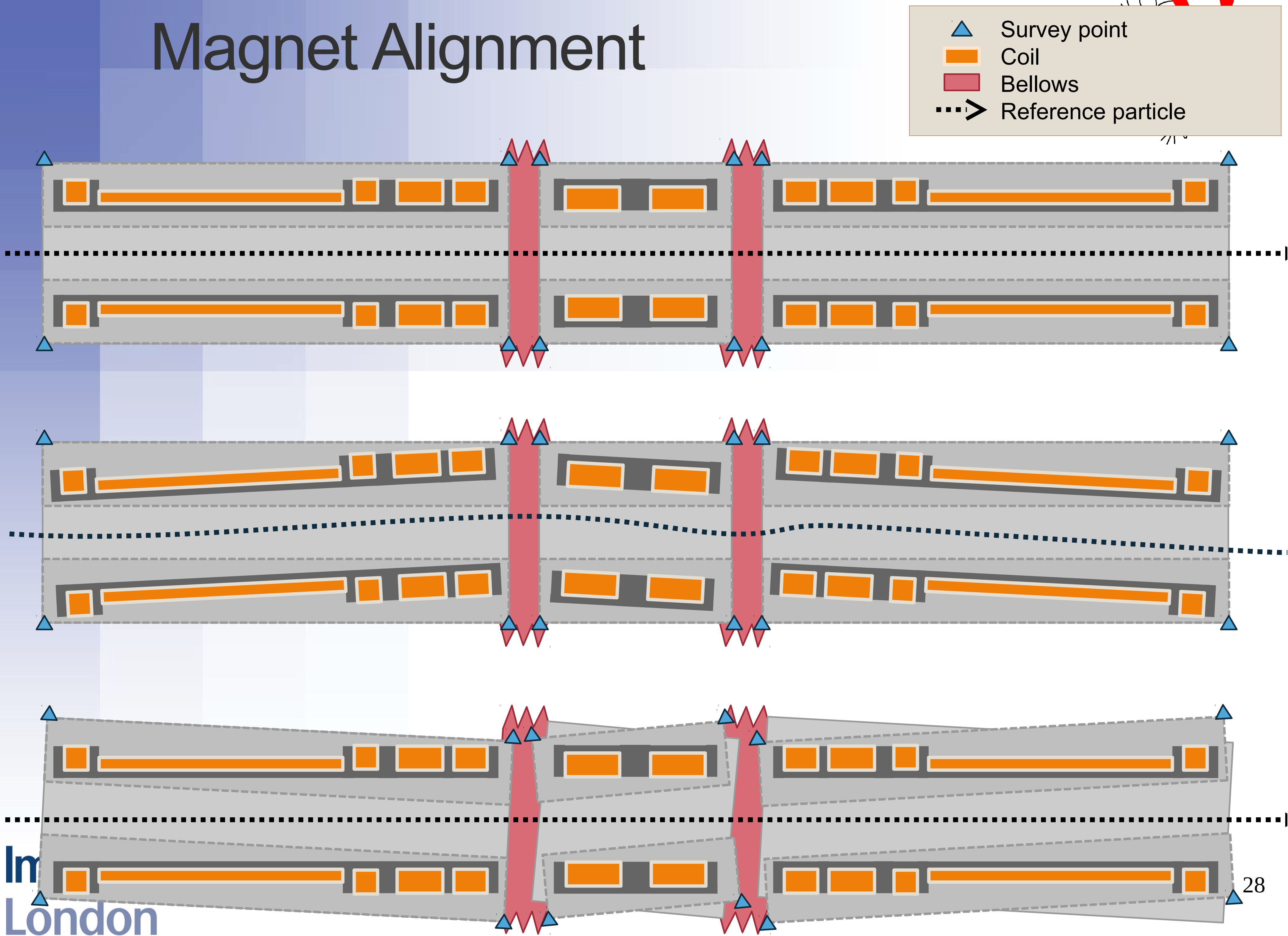


MEASUREMENT OF THE MAGNETIC AXIS

SSU, SSD, FC2 AND FC1

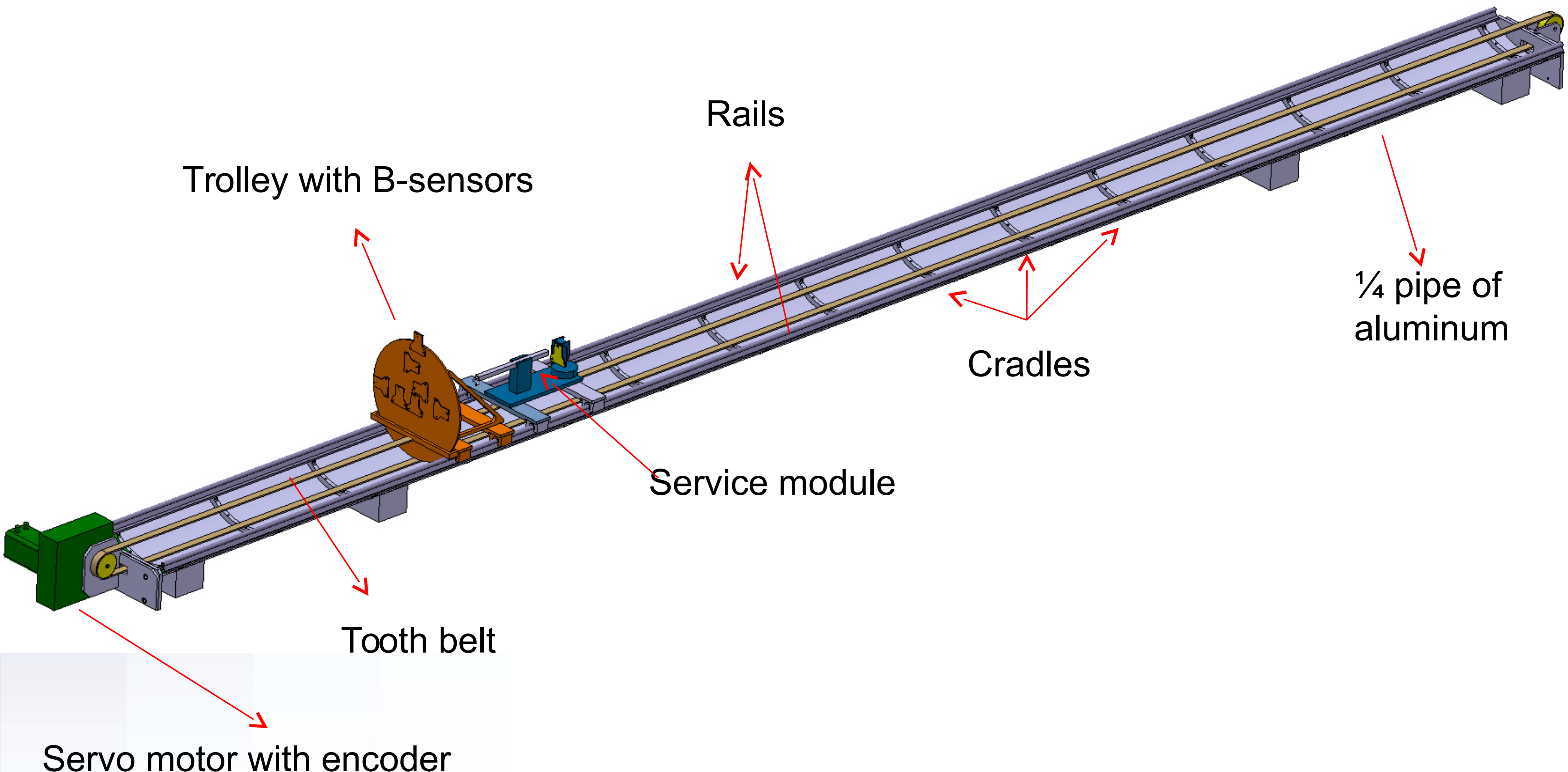
Thanks to Victoria Blackmore

Magnet Alignment



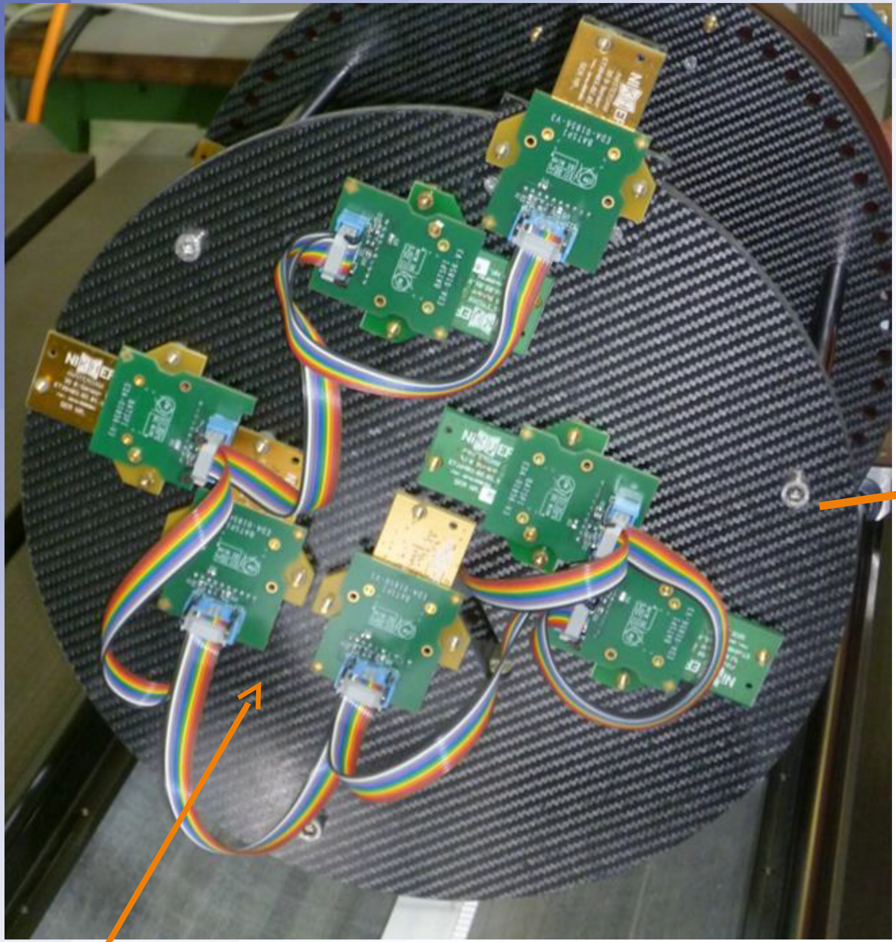
Thanks to Victoria Blackmore

CERN Field Mapper

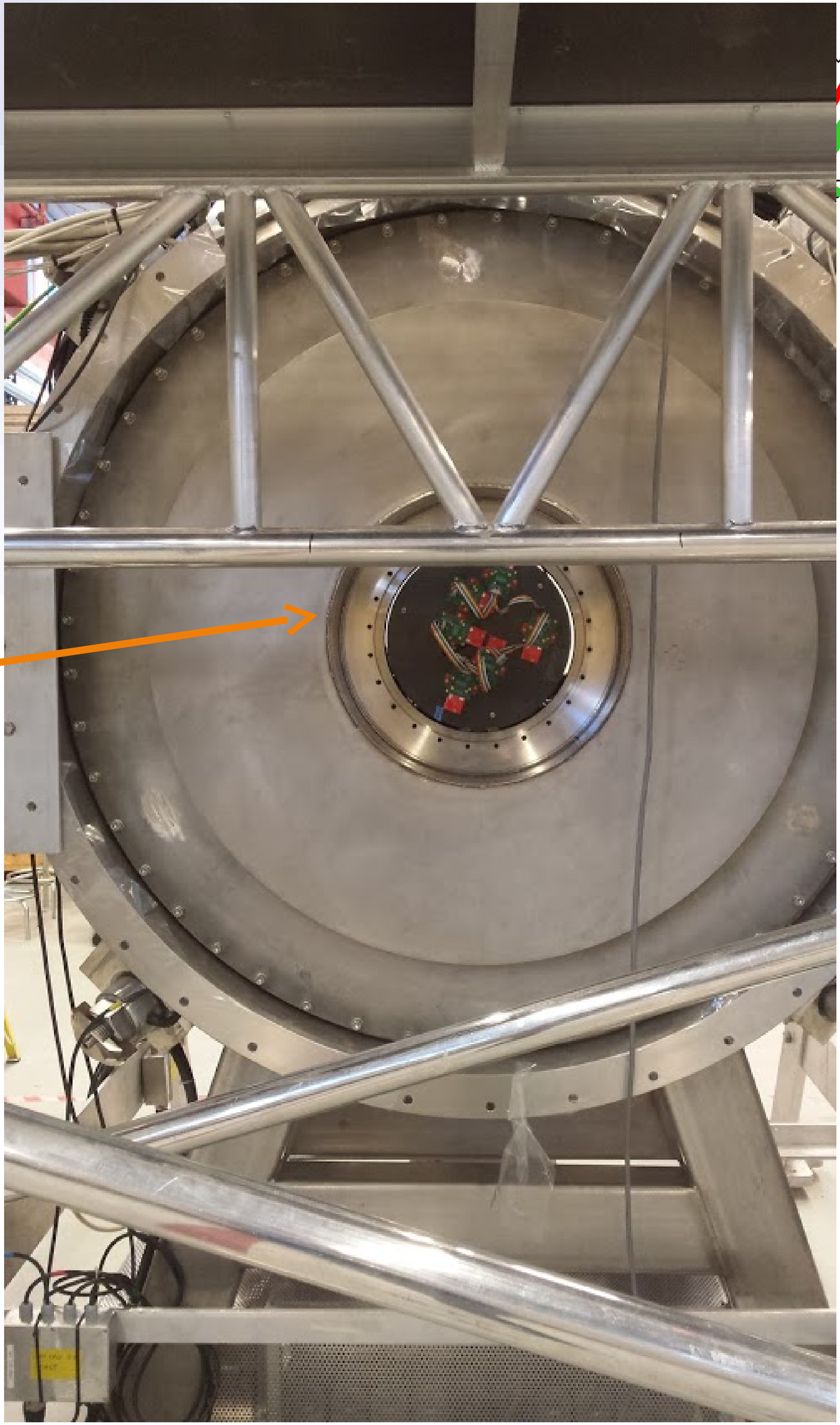


Thanks to Victoria Blackmore

CERN Field Mapper



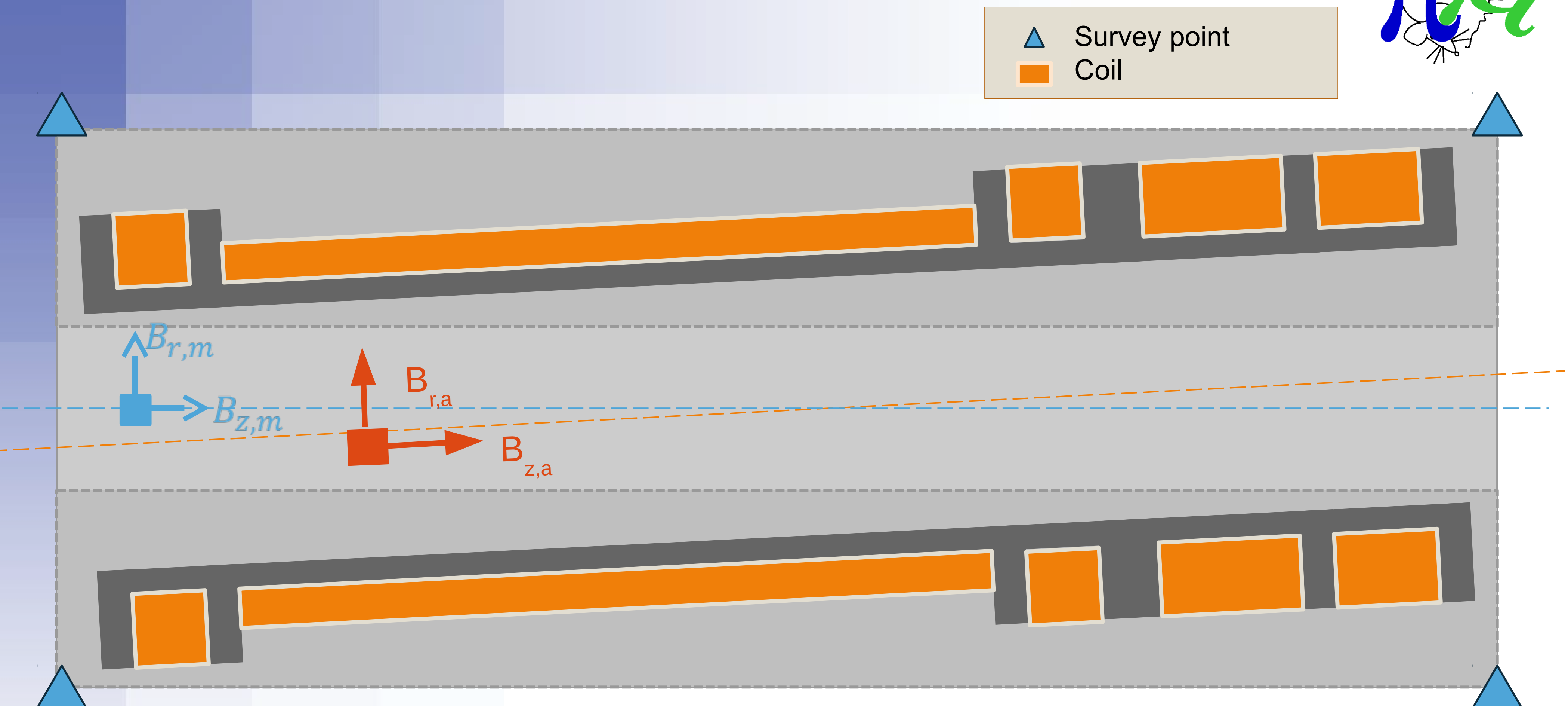
3-axis Hall probes measure B_r, B_φ, B_z



CERN Mapper in FC2

Thanks to Victoria Blackmore

Magnet Alignment



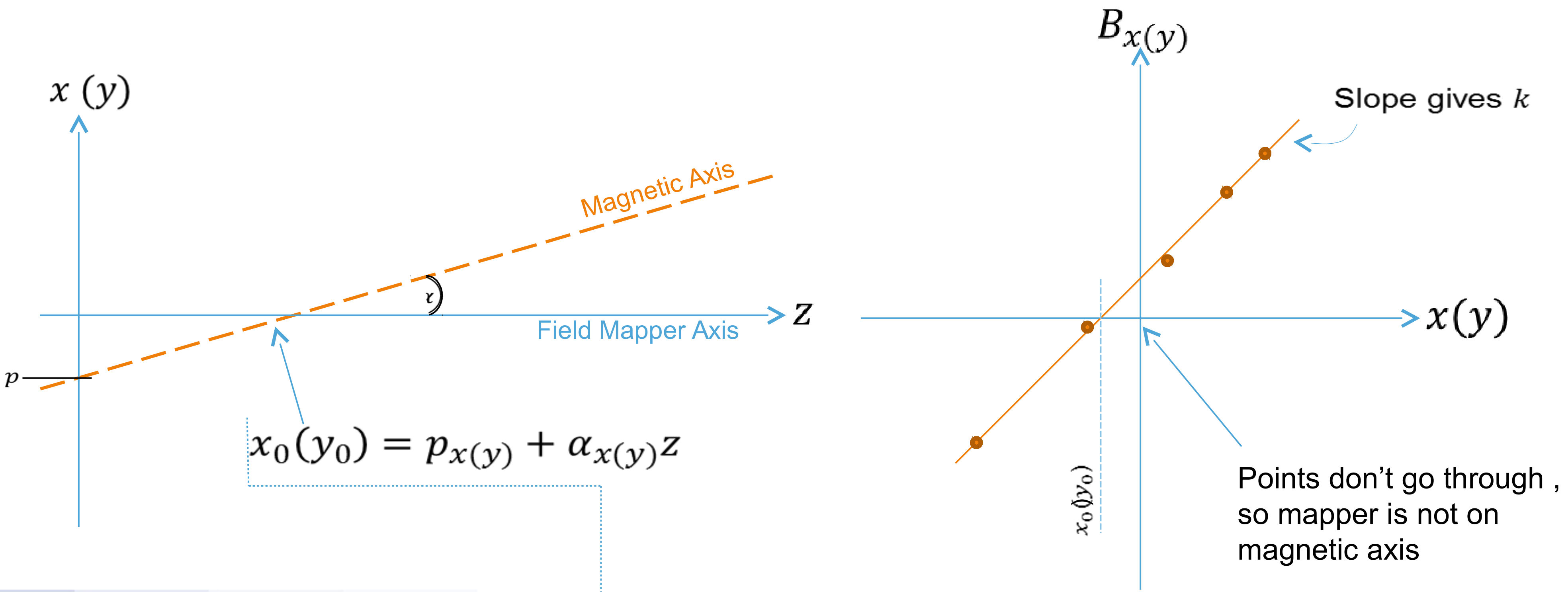
$B_{r,m} \neq B_{r,a}$

$B_{z,m} \neq B_{z,a}$

$B_{r,m}$ and $B_{z,m}$ are measured by the field mapper
$B_{r,a}$ and $B_{z,a}$ are the true axial values
→ Find the angle and offset between these values

Thanks to Victoria Blackmore

Method 1



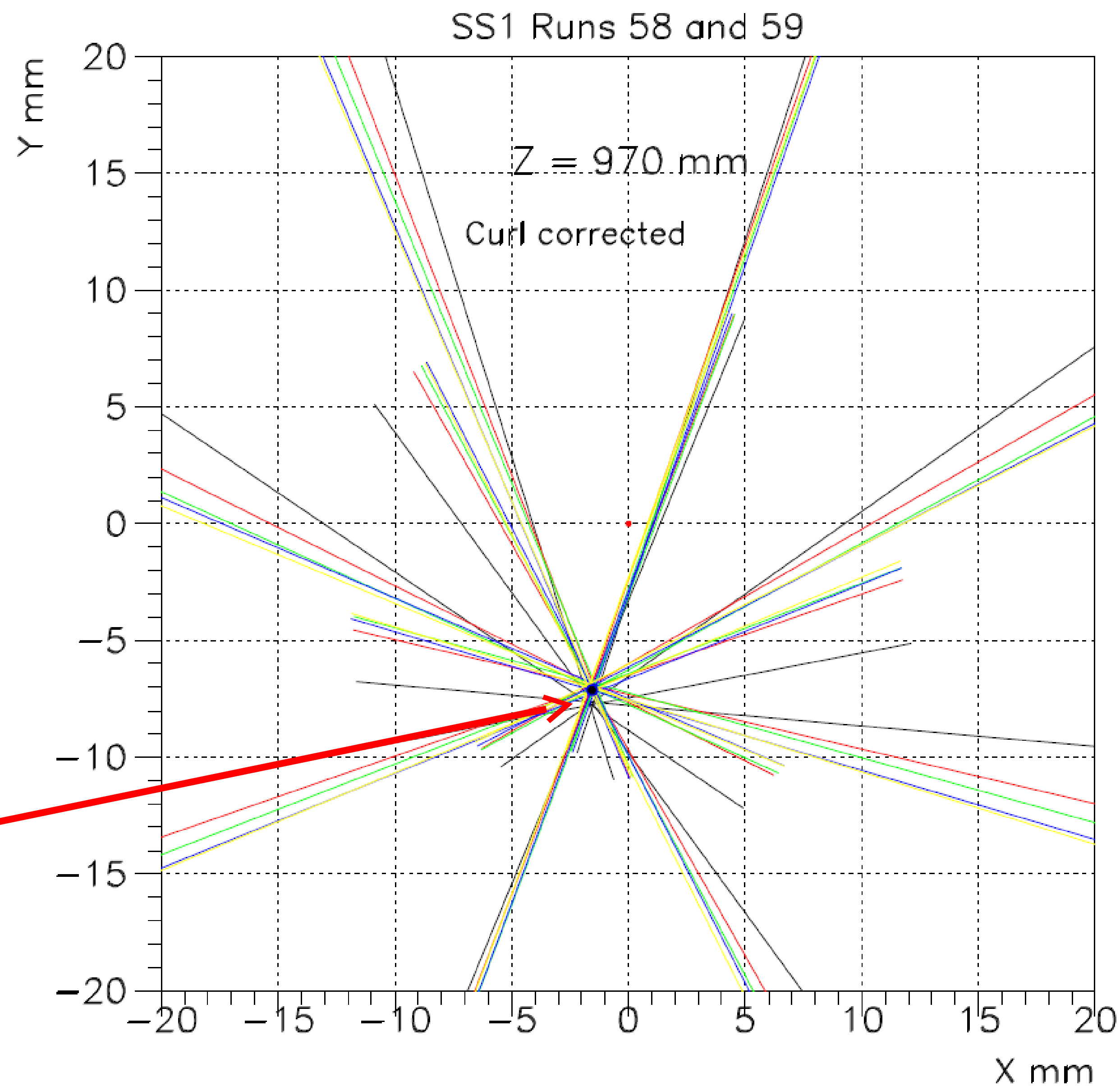
- Magnetic axis is tilted w.r.t. Hall probes/mapper
- Measure field in mapper system
- At each z, look at (x, B_x) and (y, B_y)

- In x, mapper measures $B_x = k(z)(x - x_0) + \alpha B_z$ (and similar for y)
- Find k at each z, then find best p, α across all measurements.
- p, α define the magnetic axis

Thanks to Victoria Blackmore

Method 2

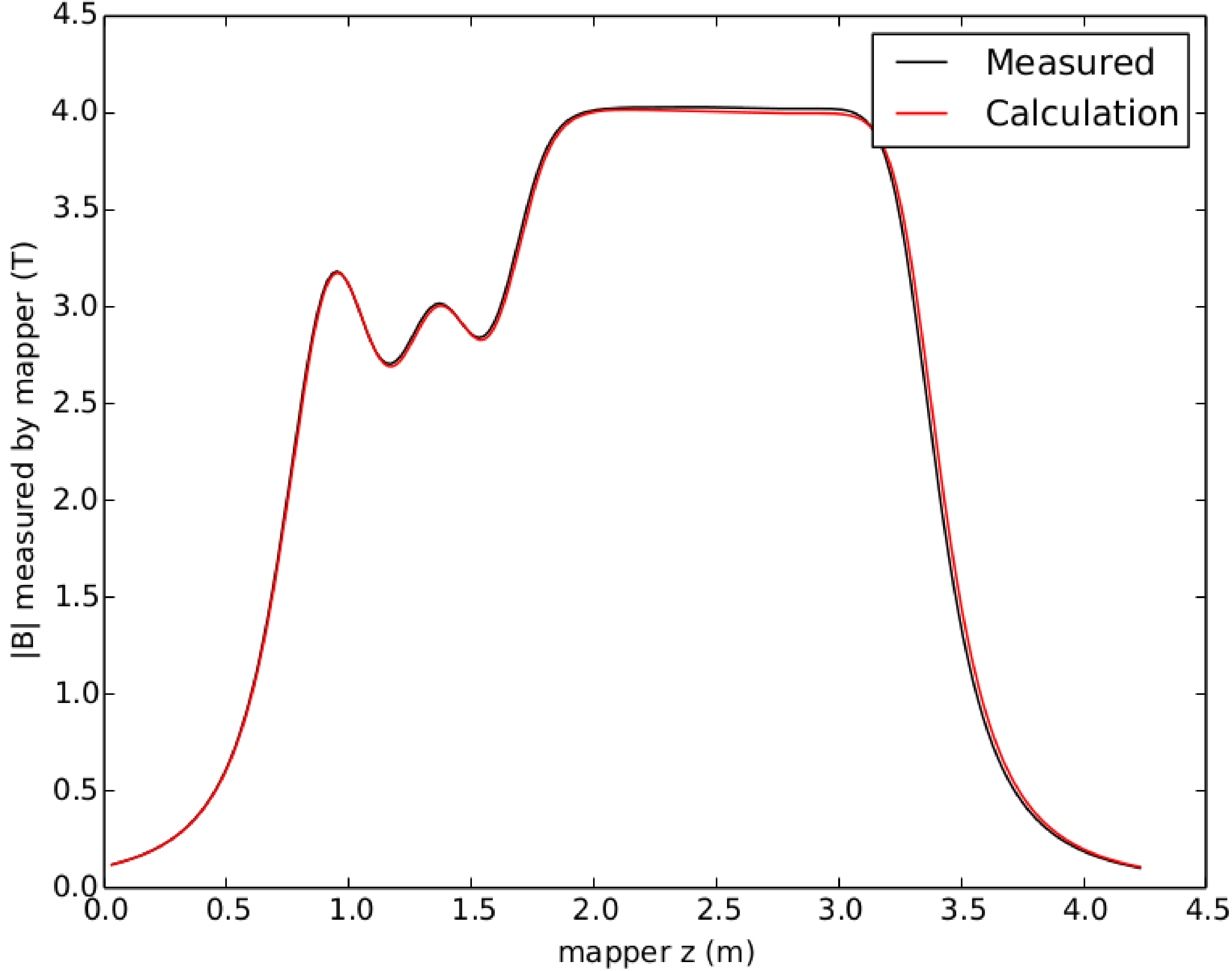
- Look at the transverse field vectors.
- vectors point to the magnetic axis.
- Lines along the transverse field vectors measured by all Hall probes at one z (970mm in mapper coordinates)



Best fit vertex

Plots are SSD data

SSU Measured vs Calculated field



Magnet Alignment

- We have measured the positions of the magnetic axes to < 1 mm.
- Data taken with only SSD powered
  - Cross check magnetic analysis with beam
  - Preliminary result is consistent with magnetic analysis
- 'Correcting' bellows may be constructed for the Demonstration of Ionisation Cooling, to improve the magnetic axis alignment further.

Thanks to Victoria Blackmore

Magnet Readiness

- All magnets are fully tested and have been individually trained (outside of the MICE experimental hall).
- All magnets are installed.
- Magnet training in situ has begun.
- Magnet training is due to be complete in the next few months.

Conclusions

- MICE has two Tracker detectors to measure the beam emittance before and after cooling.
- The Trackers are installed, QA'd and cosmics tested.
- Calibration and commissioning is well underway and is going well.
- Data taking has started:
  - Straight tracks for alignment.
  - Tracks with field on (during magnet training).
- Two superconducting solenoids surround the Trackers and an Alternating focus coil magnet around the absorber.
- All magnets are tested and installed.
- Magnet training is currently in progress.

Muon Ionisation Cooling

*Muon beam loses both transverse and longitudinal momentum by ionisation cooling when passed through an 'absorber'.

*Longitudinal momentum is restored by two 201 MHz RF cavities.

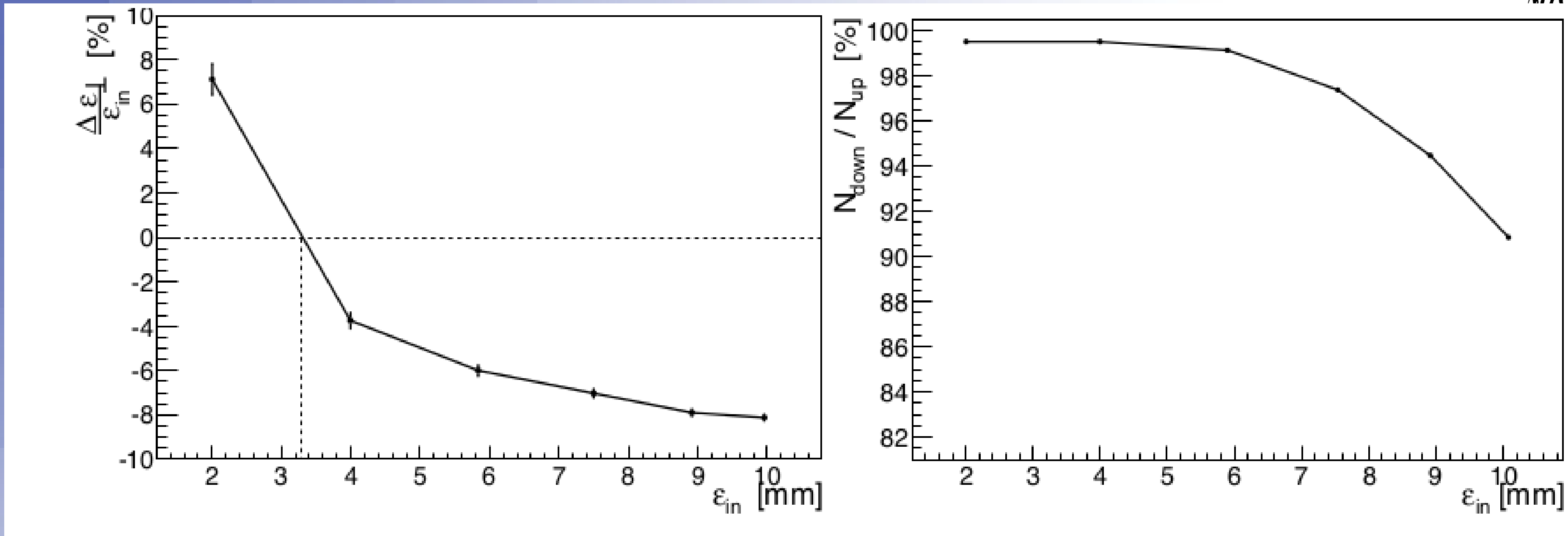
$$\frac{d\epsilon_n}{ds} \simeq -\frac{1}{\beta^2}\left\langle\frac{dE_\mu}{ds}\right\rangle\frac{\epsilon_n}{E_\mu} + \underbrace{\frac{1}{\beta^3}\frac{\beta_\perp(0.014\mathrm{GeV})^2}{2E_\mu m_\mu L_R}}_{\text{Heating through multiple scattering}}$$

$D\varepsilon_n/ds$ is the rate of change of normalised-emittance within the absorber;
β, E_μ and m_μ the muon velocity, energy, and mass respectively;
$\beta_\perp$ is the lattice betatron function at the absorber;
L_R is the radiation length of the absorber material.

*Heating through multiple scattering

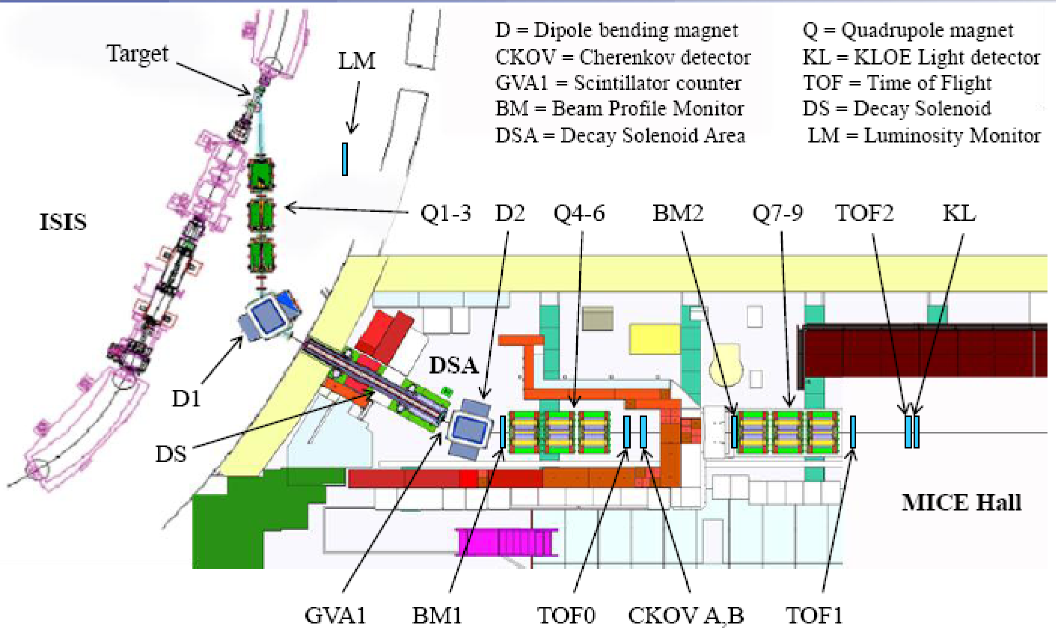
MICE aims to reduce the transverse emittance of the beam and measure the normalised emittance reduction with a precision of 0.1%.

MICE: The trade off



(left) Change in emittance, and (right) beam transmission (both in percent), vs. input emittance.

- The effect of the heating & cooling terms is an equilibrium emittance $\varepsilon_{n,eq} \propto \beta_\perp / \beta X_0 \langle dE_\mu /ds \rangle$ below which the beam cannot be cooled.
- However, as input emittance increases, beam scraping results in increased loss.
- MICE will study this in order to obtain a complete experimental characterisation of the cooling process.
- (Since a typical cooling channel will employ dozens to hundreds of cooling lattice cells, the precision with which even the tails of distributions can be predicted will have important consequences for the performance of the channel.)



The Beam

- ISIS 800 MeV proton beam.
  - delivering 4 μC of protons
  - in two 100 ns long pulses
  - With mean current of 200 μA.
- Titanium target is dipped into ISIS beamline.

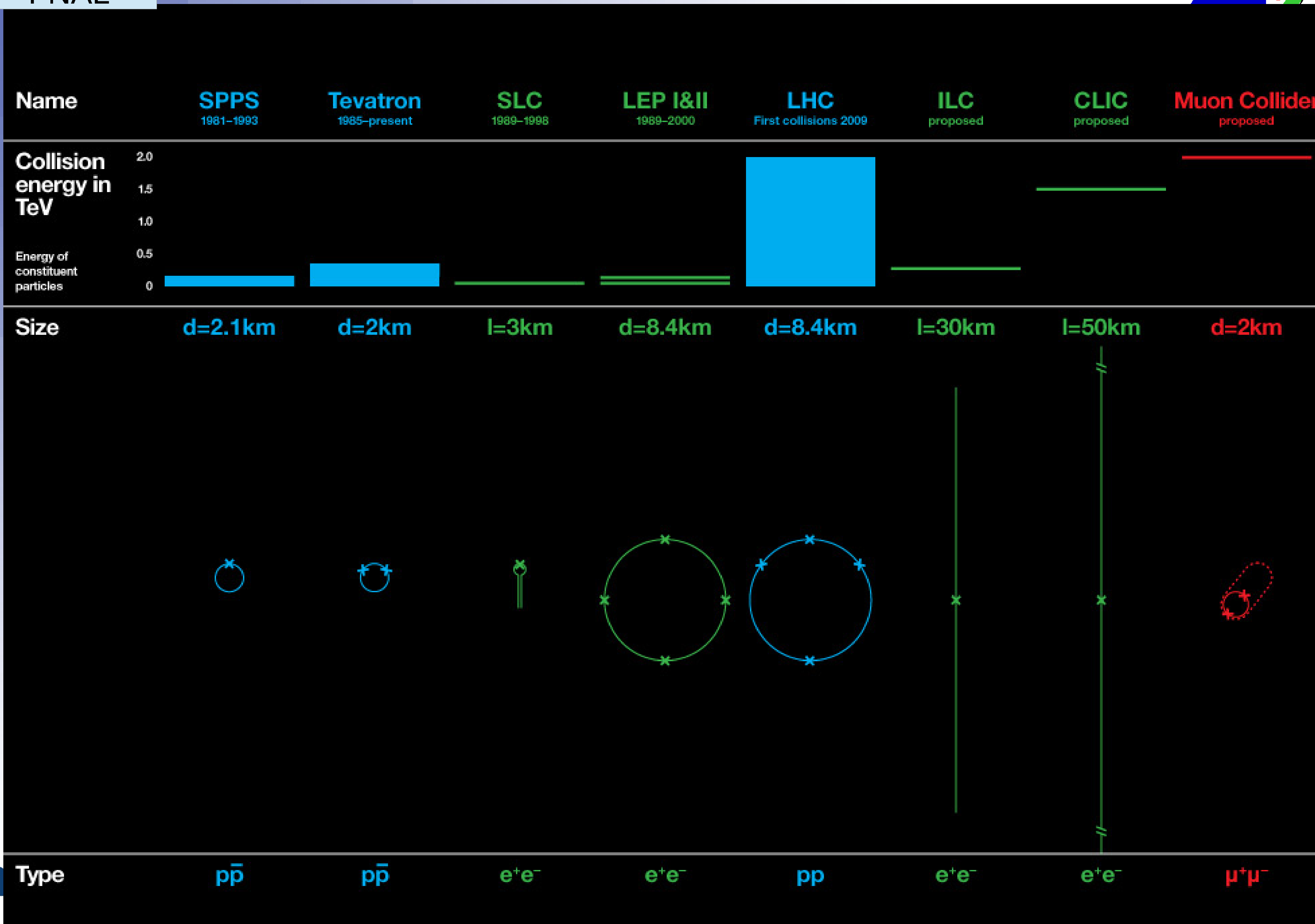
- Pions (π^+) produced in target decay to muons of lower momentum.
- Beam can be prepared as a π beam or μ beam with momenta between 140-450 MeV/c.
- Dip rate: 1 dip/2.56s
- Max Particle rate (for 1 dip/2.56s):
  - μ^+ ~120 μ/dip
  - μ^- ~20 μ/dip
- Most efficient usage delivers 850 μ/s at 1 Hz.
- Final μ beam: 1ms wide spill in 2 100ns long bursts every 324 ns.

Motivation: Muon Colliders

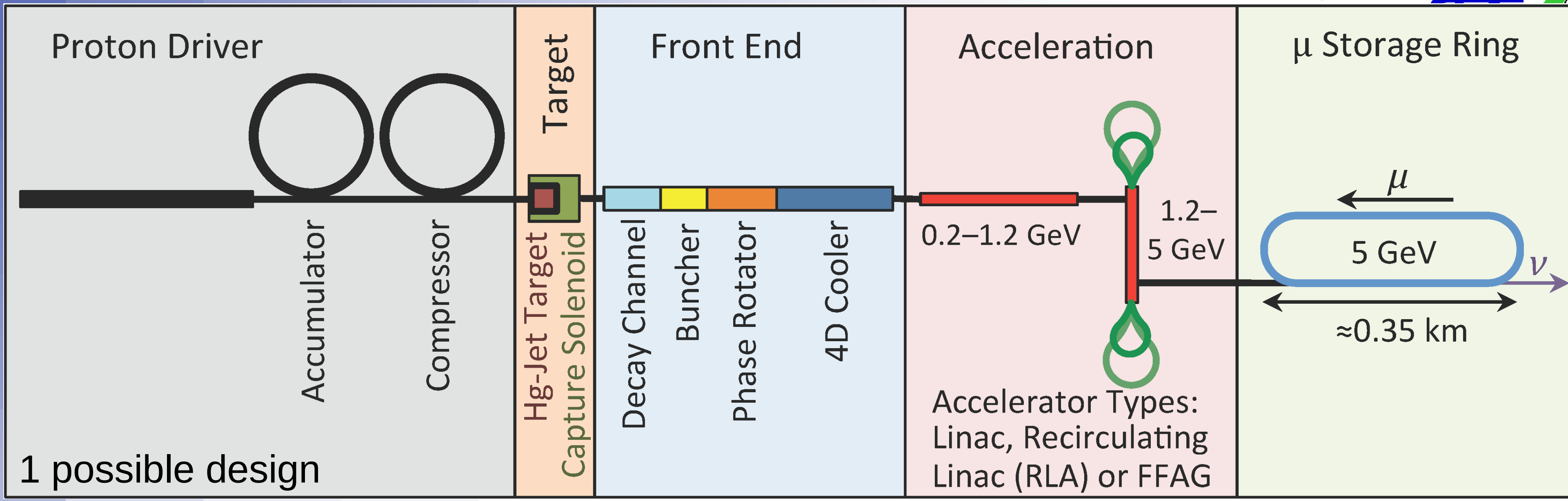
- Muons have many important advantages over electrons for high-energy lepton colliders:
  - suppression of radiative processes as $m_\mu = 207 * m_e$
  - enables the use of storage rings and recirculating accelerators
  - “Beamsthralung” effects, (radiation due to beam-beam interactions), much smaller in a muon collider than an e^+e^- machine
    - Circular e^+e^- colliders are energy limited and linear colliders are long and expensive.
  - The centre of mass energy of the collision can be precisely adjusted and the resonance structures and threshold effects studied in great detail in a muon collider.
  - Can sit on existing laboratory sites.

Borrowed from FNAL

Size Comparison of Colliders



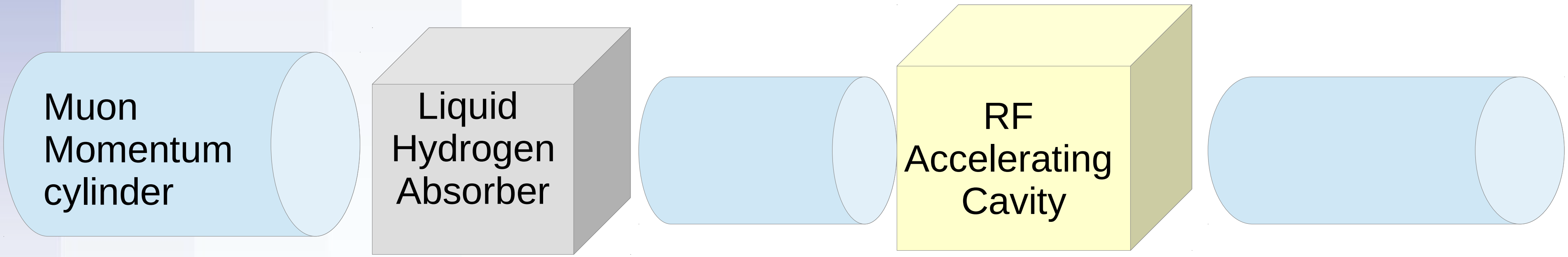
Motivation: Neutrino factory



- In order to measure δ_{CP} to 5σ we must understand the neutrino cross section to the 1% level. A neutrino factory is perhaps the most viable solution to allow us to do this.
- A muon storage ring is an ideal source for long-baseline neutrino-oscillation experiments: via $\mu^- \rightarrow e^- \nu_\mu \nu_e$ and $\mu^+ \rightarrow e^+ \nu_\mu \nu_e$
- Provides collimated, high-energy neutrino beams with well-understood composition and properties.

What is Muon Ionisation Cooling?

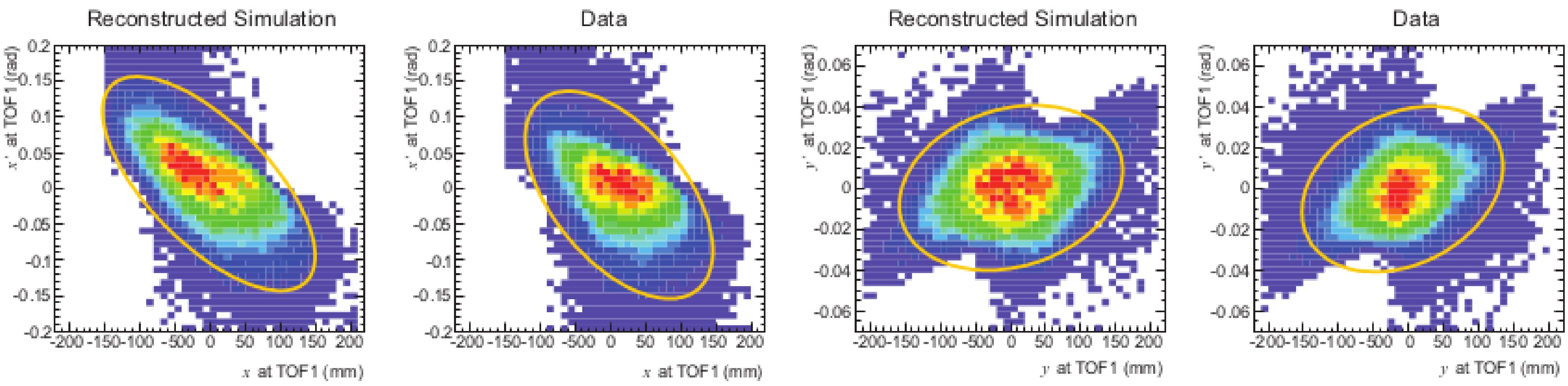
- Muons are passed through a liquid hydrogen `absorber' where they lose both longitudinal and transverse momentum as they ionise the hydrogen.
- A proportion of the lost longitudinal momentum is then restored by RF cavities.
- The result is a beam of muons with reduced transverse momentum.



- However, this process also causes some heating so the net cooling is a delicate balance between these two effects

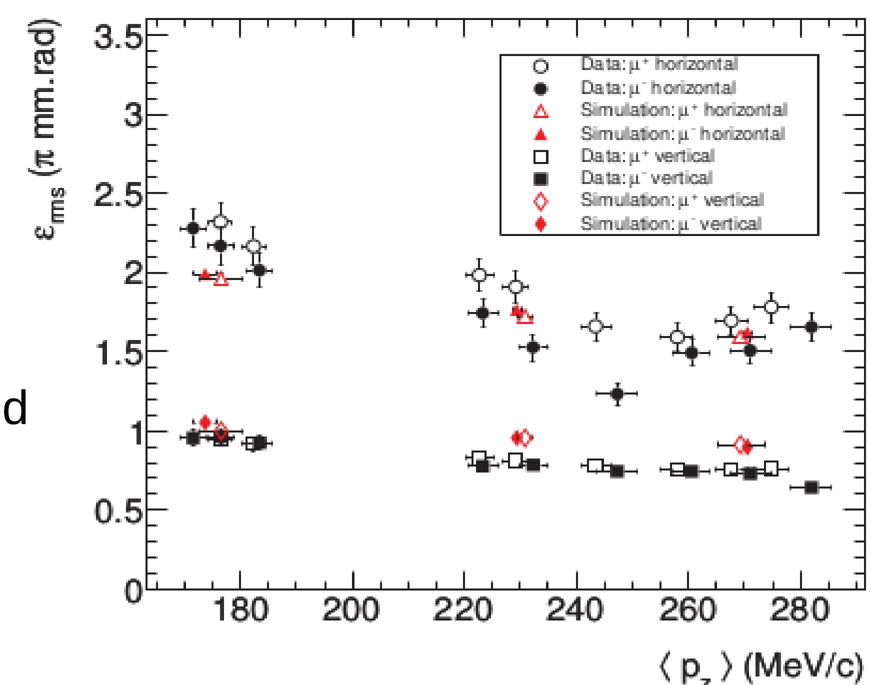
Step I

Reconstructed horizontal and vertical trace-space in simulation and data.



Horizontal and vertical RMS emittance in data and simulation.

A novel technique based on time-of-flight counters was used to establish that the beam emittances are in the range 0.6–2.8 π mm-rad, with central momenta from 170–280 MeV/c, and momentum spreads of about 25 MeV/c.



Ref. ArXiv:1306.1509

Step I

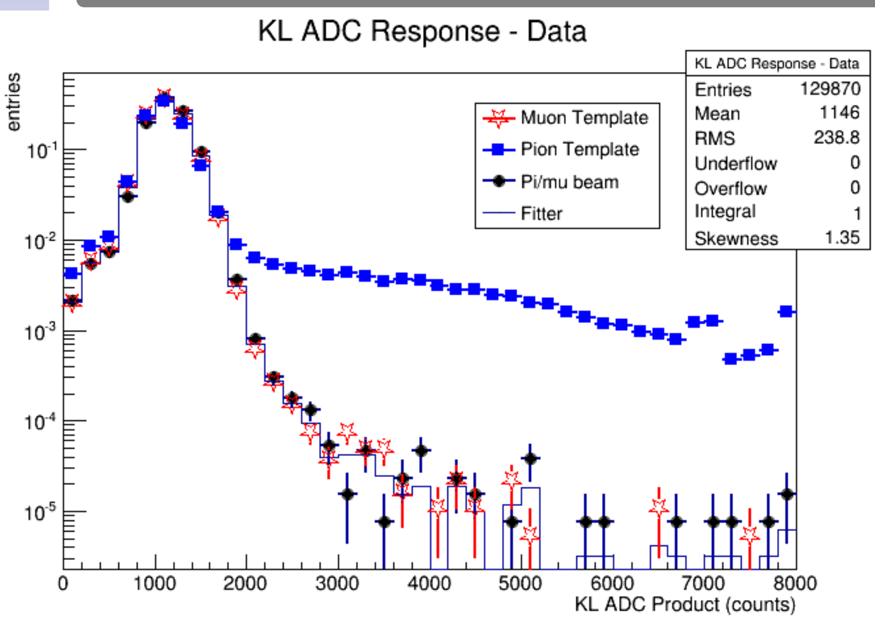
Muons per MICE target dip (spill) as a function of ISIS beam loss

μ-

ε_N (π mm · rad)	μ^- rate (muons/V· ms)		
	p_z (MeV/c)		
	140	200	240
3	4.1±0.2	6.3 ±0.2	4.9±0.2
6	4.1±0.4	4.8±0.2	4.5±0.2
10	4.6 ±0.2	5.4±0.2	4.4±0.1

μ+

ε_N (π mm · rad)	μ^+ rate (muons/V· ms)		
	p_z (MeV/c)		
	140	200	240
3	16.8±1.8	33.1±3.2	33.0±2.6
6	17.8 ±1.8	31.0±2.0	31.7±2.0
10	21.6±2.2	34.0±2.5	26.1±1.5



- Observed particle rates in TOF0 and TOF1 detectors were recorded and time-of-flight used to select good μ tracks.
- The rates are found to be linear with the ISIS beam loss/target depth.
- Errors mainly due to the time-of-flight cuts used to define a muon.
- Muons per spill is presently limited by the tolerance of the irradiation caused in ISIS by protons and secondary particles produced in the MICE target.
- Rates obtained are sufficient to collect the ~10^5 muons necessary to perform a relative measurement of cooling with a precision of 1%, in maximum one day.

Ref. ArXiv:1203.4089

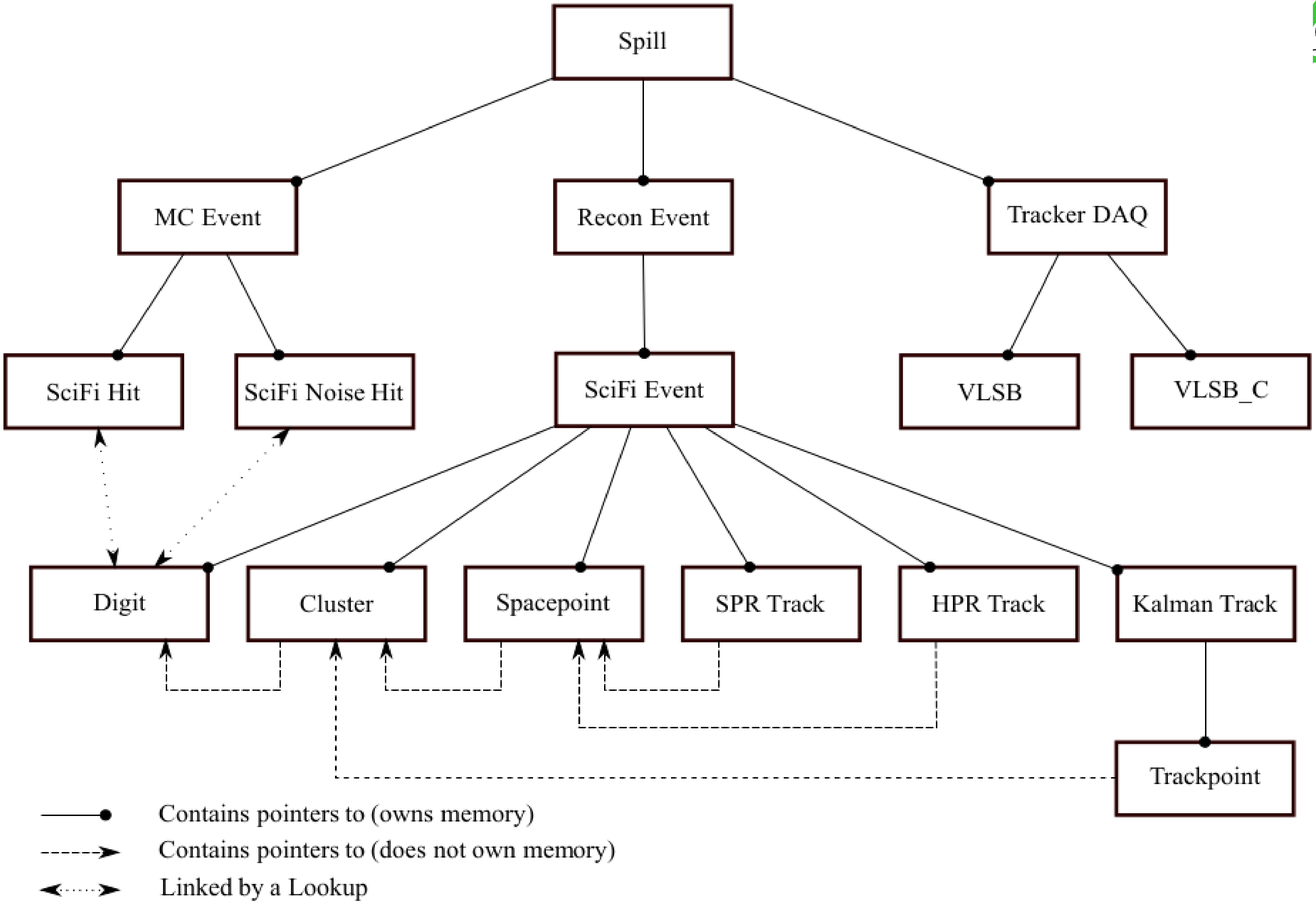
MICE Muon beam contamination

- Determination of MICE muon beam purity using the KL detector. A pion contamination in the muon beam at or below the 1% level (<5% for μ+) is determined.

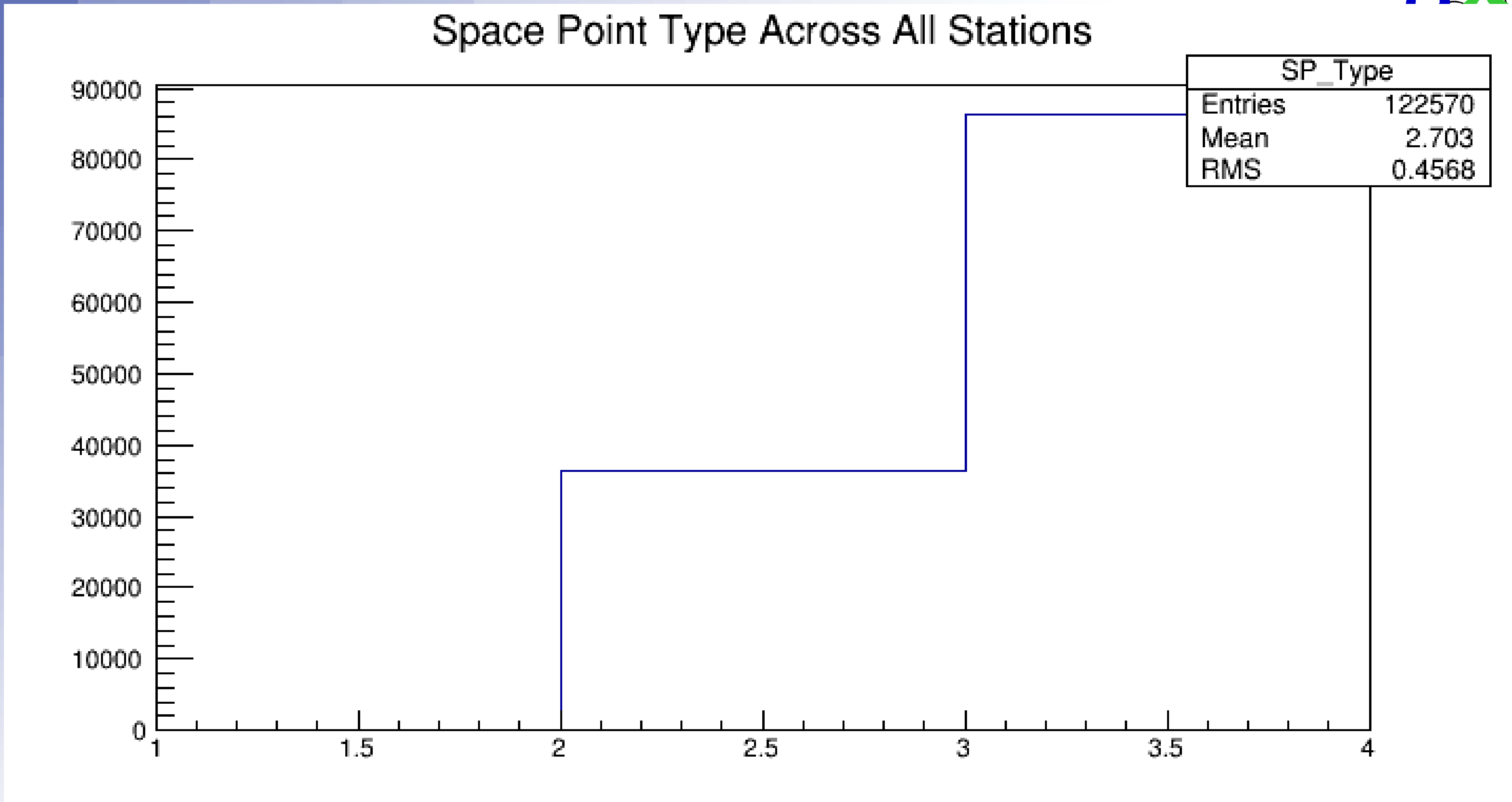
Demonstration of Ionisation Cooling

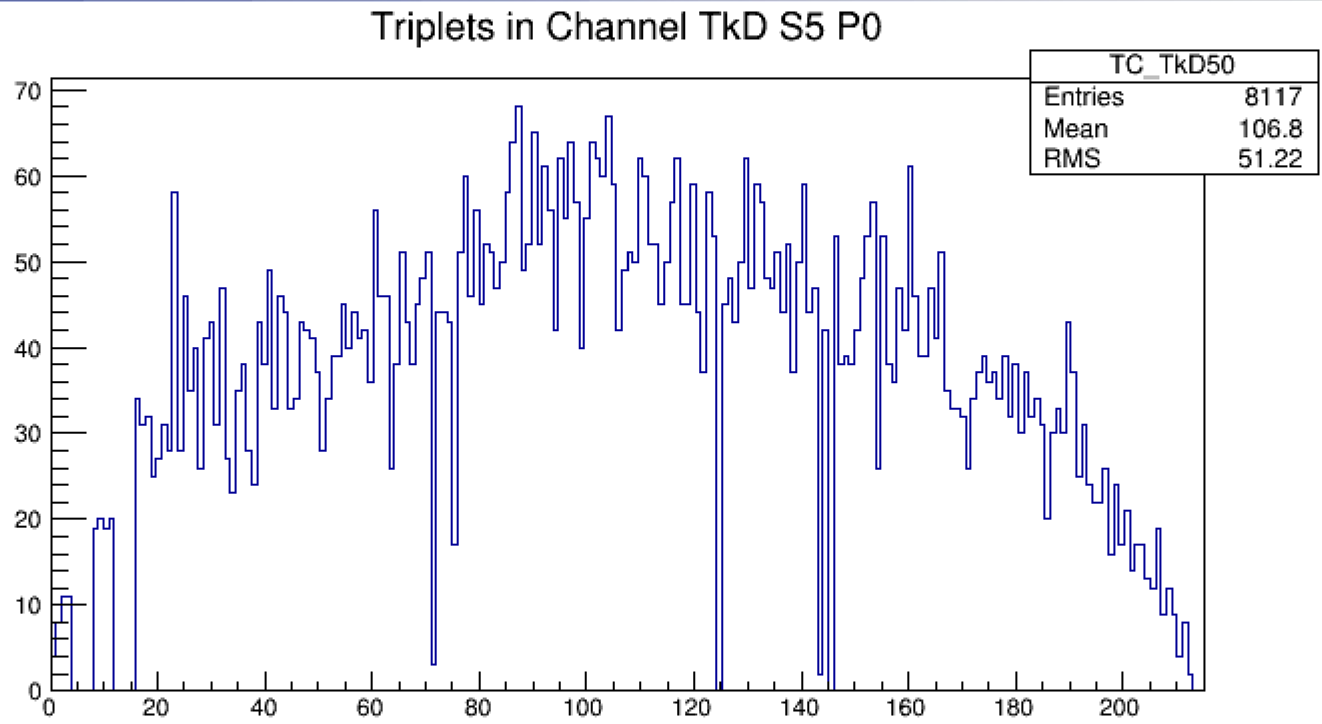
- Will vary the absorber material, magnetic focusing strength (typically 5 settings), polarity and optics configuration, beam momentum (3 settings) and emittance (3 settings)
- Absorber materials: LH 2 , empty, LiH, and possibly plastic.
- Muon momenta: 140, 200, and 240 MeV/c.
- Emittance: 3,6 and 10 π mm.rad
- At each momentum, it is important to study a variety of beam emittances and β ⊥ values, so as to sample typical cases along the length of an ionization cooling channel.
- Varying the muon polarity will also be valuable as a systematics check (most of the data points will be taken with positives).
- Muons rate reduced as synchronised to the RF waveform.

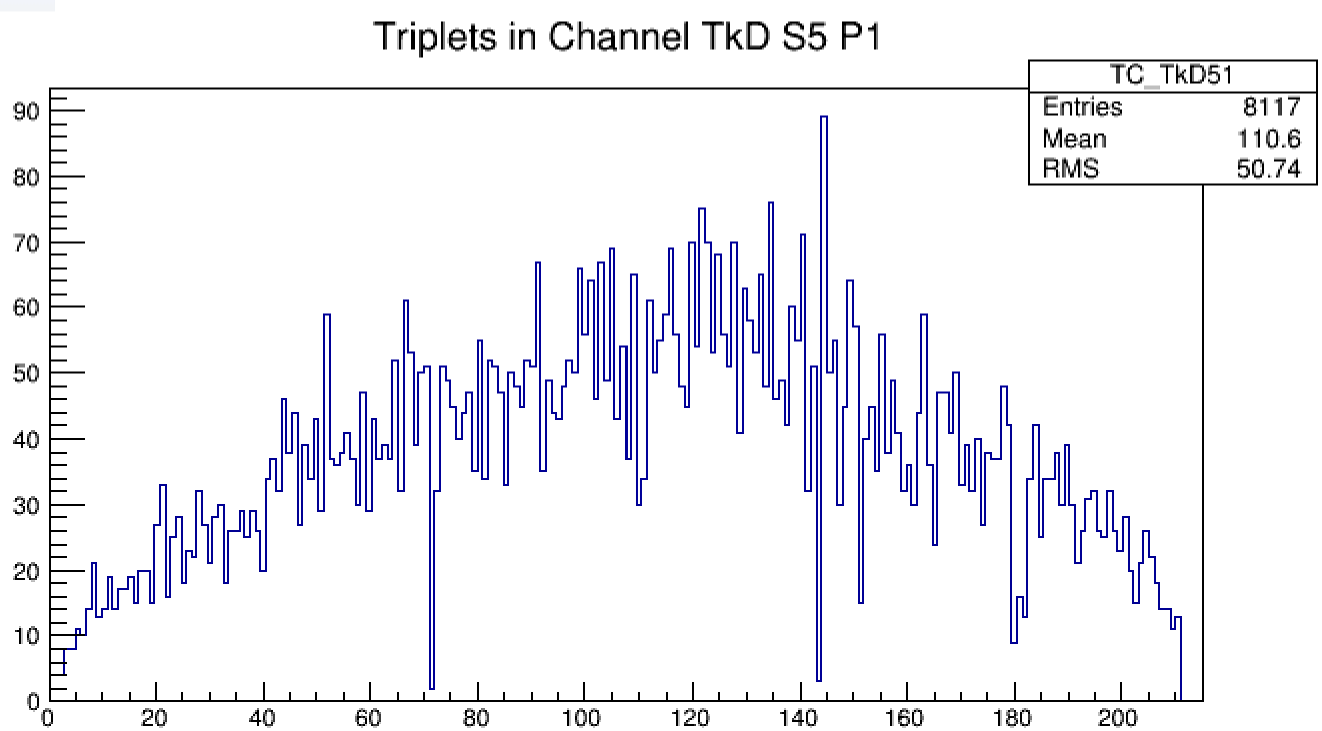
Tracker Software



Tracker Commissioning







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